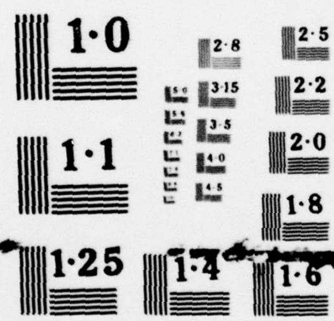
AD-A072 399 MAR INC ROCKVILLE MD F/G 8/10
A STUDY OF THE USE OF A TOWED BODY FOR OCEAN FINE AND MICROSTRU--ETC(U)
JUL 79 S H KOEPPEN N00014-79-C-0142
UNCLASSIFIED MAR-TR-226 NL

1 OF 2
AD
A072399



NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

AD A072399

MAR, INCORPORATED
1335 ROCKVILLE PIKE
ROCKVILLE, MARYLAND 20852
AREA CODE 301
424-1310

9 Technical rept.

6

A STUDY OF THE USE OF A TOWED BODY FOR OCEAN FINE AND MICROSTRUCTURE MEASUREMENT

10 S. H. Koeppen

14 MAR-TR-226

Technical Report No. 226
Contract No. N00014-79-C-0142
July 1979

15

11 Jul 79

12 104p.

Prepared for:

NAVAL OCEAN RESEARCH AND DEVELOPMENT
ACTIVITY (NORDA)
Code 500
Bay St. Louis, Mississippi 39520

390 477

ABSTRACT

A study was performed to determine if existing operational and developmental towed oceanographic measurement systems can meet, or be modified to meet, projected Navy needs for fine and microscale measurements of temperature, salinity and water velocity in the upper ocean. While no existing system presently meets the requirements for measurement of all three parameters, at least one system meets the requirements for measurement of temperature and salinity. Investigations required to determine the feasibility of a system capable of meeting the additional requirements for velocity measurement are identified.

Table of Contents

Table of Contents (Cont.)

List of Illustrations

List of Tables

List of Tables (Cont.)

Section 1

INTRODUCTION

Oceanographic studies within the past ten years have given a considerably improved understanding of the small scale structure of temperature, salinity, and water velocity in the ocean[1-10]. Such data is still relatively sparse, however, especially at the smallest scales because of the problem of deploying a stable sensor platform in the ocean environment. In order to support various non-acoustic ASW concepts, this data is needed over large portions of the ocean and NORDA has been tasked with the development of an appropriate instrumentation suite and means of collecting such data. While a variety of fine and microscale* measurement techniques have been used in the past, most researchers have used either moored instrumentation or sensors that are lowered on a line deployed from a ship or stationary platform. Expendable and towed sensors have been employed to a lesser extent. The Navy's need for large area, real-time data down to scales on the order of a centimeter narrows the alternatives to essentially three.

The first method is the use of sensors mounted on the bow of a submarine. Although this method fulfills the wide area, real-time data requirement, it imposes constraints on an operational submarine, and the availability of a submarine dedicated to a measurement program is highly unlikely.

---

*While there is no standard definition of fine and microscales, microscales are defined here as < 0.5 m and finescales as 0.5 - 50 m. These definitions are in general agreement with the terminology in the oceanographic literature and cover the range of scales of interest to NORDA.

The second method is to tow a vertical array of sensors from a ship. Problems with this technique include high expense, handling problems, relatively low tow speed, and tow cable/sensor motion problems.

The third method is to mount the sensors on a towed or free swimming body deployed from a surface ship. A major advantage of this type of sensor platform is the capability of positive control over the depth of the sensor. Because of this and other advantages including relatively high speed capability, ease of deployment and operation, and cost advantages, at least for the towed body, this technique appears most feasible for large area, real-time collection of fine and microstructure data. This report describes the results of a study performed by MAR, Incorporated for NORDA, Code 500, to determine if existing towed oceanographic measurement systems can meet, or can be modified to meet, projected Navy requirements for measurement of the finestructure and microstructure of temperature, salinity and velocity in the upper ocean.

The approach to the study consisted of three tasks:

1. Identification of requirements,
2. Documentation of capabilities, and
3. Evaluation of alternative systems.

The following sections discuss the approach to and results of each of these tasks in detail.

Section 2

REQUIREMENTS

2.1 APPROACH

A three part approach was taken to identify system requirements. First, all relevant characteristics of both instrumentation and towed body systems were identified and categorized. Second, the minimal set of these characteristics whose specification was considered necessary to be able to compare and evaluate the measurement capability of existing systems was identified. Last, requirements for this primary set of characteristics were specified or quantified based on available Navy documentation[26] and existing oceanographic data. The specification of requirements for the remaining system characteristics is not really appropriate or even possible at this time because the majority of them are details which do not impact overall measurement feasibility but rather belong in a design study, once the basic type of measurement system is chosen.

2.2 INSTRUMENTATION AND TOWED BODY SYSTEM CHARACTERISTICS

Tables 2-1 and 2-2 list fine and microstructure instrument characteristics and towed body system characteristics respectively. The categories marked with red are those which contain the characteristics considered to be of primary importance, namely:

1. Speed range
2. Depth range
3. Body motion control
4. Body motion monitoring
5. Measurement specifications for T, S and v

Table 2-1. Fine and Microstructure Sensor/Instrument Characteristics

I. MEASUREMENT CHARACTERISTICS

A. Range

B. Accuracy

C. Resolution

D. Response Time

E. Spatial Resolution

F. Stability

G. Principle of Operation

II. PHYSICAL CHARACTERISTICS

A. Dimensions

B. Material

C. Weight

III. ELECTRICAL CHARACTERISTICS

A. Power

B. Telemetry

C. Noise

IV. OPERATIONAL INFORMATION

A. Environmental Limitations

B. Calibration

Table 2-2. Towed Body System Characteristics

I. PHYSICAL CHARACTERISTICS

A. Wind Span (S)/Chord (C)

B. Body Length (L)

C. Minimum Rectangular Volume (L x S x Height)

D. Air Weight

F. Virtual Mass

G. Center of Gravity (Relative to Towpoint)

H. Center of Buoyancy (Relative to Towpoint)

II. OPERATIONAL CHARACTERISTICS

A. Design Speed Regime

B. Maximum Design Depth (Pressure)

C. Maximum Towstaff Tension and Angle (Relative to Flow) vs Towspeed (if available) or

D. Depressor Depth vs Speed (include Towcable Characteristics or diameter, Weight per Foot (in Air and Water), and Length)

E. Maximum/Minimum Depth Change vs Towspeed

F. Maximum/Minimum Rate of Change of Depth vs Speed

III. DESIGN FEATURES

A. Motion Control and Monitoring

1. Passive Control - Speed and Cable Scope for Depth
2. Active Control - Moveable Control Surfaces
3. Monitoring Instrumentation

Table 2-2. Towed Body System Characteristics (Cont.)

B. Type of Cable Used

1. Material and Diameter
2. Weight per Foot in Air and Water
3. Number of Conductor and Type

C. Method of Data Transfer from Depressor and/or Oceanographic Instrumentation

1. Direct Transfer
2. Telemetry (Type)

D. Type and Amount of Total Power Required

1. AC or DC and Voltage
2 Power Requirements (Watts)

E. Handling and Storage System

1. Method
2. Weight and Volume
3. Power Requirements

IV. DESIGN FLEXIBILITY

A. Excess Dry Volume for Storage of Oceanographic Instrumentation and/or Motion Sensing Equipment

B. Method of Accommodating Future Oceanogragraphic Instrumentation

C. Extra Telemetry Channels and/or Spare Towcable Conductors

The following subsection discusses the specification or quantification of these characteristics and the associated rationale.

2.3 SPECIFICATION/QUANTIFICATION OF PRIMARY SYSTEM CHARACTERISTICS

Table 2-3 lists the primary system characteristics, a specification of requirements for those characteristics, and the impact of a capability less than that specified. Numbers given should be considered approximate rather than firm requirements. The basis and rationale for the requirements specified are discussed in the following.

Speed Range

Minimum speed is based on the approximate minimum maneuverable speed of typical oceanographic survey ships. Upper limit is based on a combination of typical cruising speeds, complexity of towed body systems at higher speeds, and practical upper limits on the frequency response of sensors needed to measure centimeter scale phenomena.

Depth Range

The depth range is that of interest to NORDA, the shallow limit being essentially one of the practicality of towing a body near the surface.

Body Motion Controllability

Is is well known that unsteady sensor motions contaminate velocity measurements directly and temperature and conductivity measurements through motion in the presence of a gradient. The requirement on allowable motion levels specified in Table 2-3 stems from this fact. The actual magnitude of the allowable motion levels thus depends on the required sensor

Table 2-3. Specification/Quantification of Most Important System Characteristics

System Characteristic	Requirements	Impact of Decreased Capability
Speed Range	2 to 8-12 knots	Longer measurement time; time variation of data
Depth Range	10 to 300-500 meters	Limited vertical coverage
Body Motion Controllability		
Allowable heave, surge, sway, pitch, roll and yaw levels	Such that: (1) resulting sensor motion effects are negligible (less than sensor resolution) or (2) sensor motion effects can be compensated to a negligible level	Contamination of data
Depth Control	$\pm$ 0.5 m of desired depth	Contamination from vertical structure
	Full range porpoising; isobar and isopycnal following	Limited horizontal/vertical profiling capability

Table 2-3. Specification/Quantification of Most Important System Characteristics (Cont.)

System Characteristic	Requirements	Impact of Decreased Capability
<u>Body Motion Measurement Instrumentation</u>	Linear and angular measurements sufficient to calculate sensor motions over frequency range of sensor response.	Uncertainty of contamination levels; inability to compensate for motion effects.
<u>Instrumentation Measurement specifications</u>		
Range:	T: $-4^{\circ}C$ to $+30^{\circ}C$ C: 25 to 70 mmhos/cm v: 0 to 8-12 knots	Limited coverage of oceanographic conditions in upper ocean.
Resolution:	T: † C: † v: †	Inability to detect lower fluctuation levels
Absolute Accuracy (At Zero Frequency):	T: $\pm 0.02^{\circ}C$ C: ± 0.5 mmhos/cm v: ± 0.5 cm/s	Uncertainty in depth of a given isopleth $> 1m$
Spatial Resolution:	T: † C: † v: †	Inability to observe dissipation peak in spectrum

† Discussed in Text

resolution which is discussed below under measurement specifications. While the removal of sensor motions from data using accelerometer measurements is presently a controversial issue, the requirement as stated is nonetheless valid.

The various modes of depth control specified in Table 2-3 stem from the following needs:

1. Porpoising: Needed to obtain vertical ocean structure. Among other things, this is needed to identify finestructure inversions in T and S which are strongly correlated with the generation of microstructure patches.

2. Isobar (constant pressure depth) following: Useful in observing vertical displacement of isopycnal surfaces due to internal waves. Also the quietest mode of operation in terms of body motions.

3. Isopycnal following: Needed in order to investigate the horizontal extent and frequency of occurrence of microstructure patches which lie along a constant density surface.

While the exact value of allowable depth variation depends on the strength of the vertical gradients and the required sensor resolution, as mentioned above, it is possible to specify an approximate value of $\pm$ 0.5 m based on the following argument. In general, the largest depth excursions will be at the frequency of the ship motion or at the natural oscillation period of the towed system which are quite low relative to the frequencies corresponding to microstructure scales when towing at several knots speed. For smooth depth excursions and vertical structure which does not vary too rapidly over the depth change, these excursions will contribute little energy

at microstructure frequencies. As it turns out, the vertical finestructure of the ocean has a cut-off at a scale of about 1 m, that is, the vertical correlation distance is on the order of 1 m[6,7]. Consequently, if the vertical motion is less than this, we would expect the contamination to be narrow-band at the frequency of the body motion. This is in fact the case as is illustrated schematically in Figure 2-1 where $W_{T'}$ is the horizontal temperature gradient spectrum and f_λ is the spatial frequency in cycles per meter (cpm). If we take temperature as an example and write the vertical temperature profile as

$$T(z) = (z - z_o)\overline{T'} + \theta(z)$$

where $\overline{T'}$ is the mean vertical gradient and $\theta(z)$ is the fluctuating component, that is, the finestructure, then for a sinusoidal body oscillation of amplitude A and spatial period λ_o, and a vertical temperature correlation distance L_θ, the contamination of the horizontal temperature gradient spectrum $W_{T'}$ contains two terms[4,5]. The first term, the contribution from the mean gradient, is equal to

$$2\pi^2 f_{\lambda_o}^{\,2} (A\,\overline{T'})^2\, \delta(f_\lambda - f_{\lambda_o})$$

where $f_{\lambda_o} = 1/\lambda_o$ is the spatial frequency of the body oscillation. Thus contamination from this term occurs only at the body oscillation frequency which is relatively easy to discriminate against. The second term, the vertical finestructure contamination, is more complicated. For the limiting cases $A << L_\theta$ and $A >> L_\theta$ one finds that the contamination is given by

$$4\pi^2 f_{\lambda_o}^{\,2} \frac{A}{L_\theta}\, \overline{\theta^2}\, \delta(f_\lambda - f_{\lambda_o}) \qquad (A << L_\theta)$$

$$2\pi \frac{A}{\lambda_o} W_{\theta'}\left(f_\lambda \frac{\lambda_o}{2\pi A}\right) \qquad (A >> L_\theta)$$

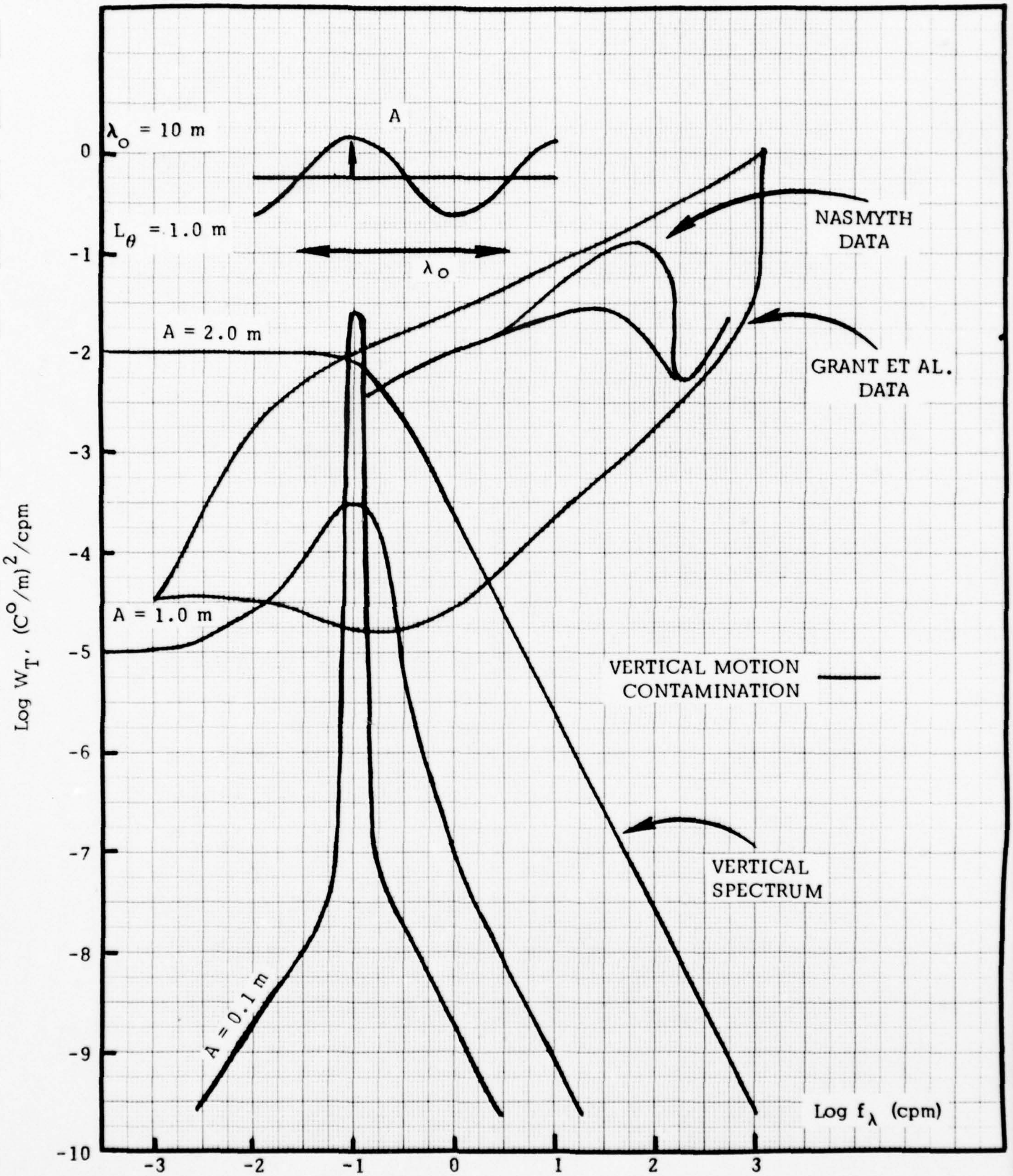


Figure 2-1. Horizontal Temperature Gradient Spectra Contamination (Schematic)

where $W_{\theta'}(f_\lambda)$ is the vertical temperature gradient spectrum. It can be seen that as the amplitude A increases, the contamination changes from narrowband at $f_\lambda = f_{\lambda o}$ to broadband, proportion to the actual vertical spectrum. Figure 2-1 illustrates this schematically. The vertical spectrum curve is that for an exponential autocorrelation function $e^{-|z|/L_\theta}$ with typical values $L_\theta = 1$ m and $d\theta/dz_{rms} = 0.05\ C^o/m$[2,7]. The green curve is an envelope of towed data taken by Grant et al.[11] while the blue curves are towed data from two microstructure patches taken by Nasmyth[11]. The purpose of the data curves is to show the relative strength of the potential contamination at different scales. It is seen that the finescale contamination is more severe than the microscale contamination. This illustration points out that it is important to know the vertical structure in order to determine, as a function of scale size, whether or not one is actually measuring horizontal structure and not contamination from vertical structure. The $\pm$ 0.5 m depth control specified is essentially the condition that $A \leq L_\theta$. In ocean areas where $L_\theta > 1$ m or the vertical finestructure is weaker, this condition could be relaxed, depending on the intensity of the horizontal structure present. In other words, the strength of the vertical structure combined with the degree of depth control determines the limiting horizontal fluctuation intensity which can be measured as a function of scale size.

It is evident from the above discussion that system requirements are strongly dependent on measurement requirements which, in turn, are strongly dependent on the nature of the phenomena to be measured. While considerable data has been collected on microstructure and finestructure, our knowledge of the statistics of the horizontal and vertical variability of the ocean is presently too limited to be able to say what percentage of fine and microscale phenomena can be measured, given a certain sensor and towed body capability. This is, in fact, one of the types of data of interest to the Navy for which a towed system would be used.

Body Motion Measurement Instrumentation

In view of the above discussion, the need for appropriate linear and angular motion sensors to be able to calculate sensor motion is evident. While a detailed discussion of motion sensors is beyond the scope of this study, the basic sensors needed are: (1) a sensitive depth transducer ($\sim$ 10 cm resolution) to support T and C measurements and (2) a linear accelerometer for each axis of v measured. The motion sensors obviously need to be as close to the oceanographic sensors as possible to be indicative of sensor motion. Provided the latter is the case, then angular motion sensors are only needed to analyze and relate overall body motion to sensor motion.

Instrumentation Measurement Specifications

Since conductivity is the ocean parameter actually measured rather than salinity, specifications for T, C and v were considered rather than T, S and v. The measurement range specifications given in Table 2-3 are based on the normal range of oceanographic conditions found in the upper 500 m of the ocean. Accuracies are based on the ability to determine a given density or current isopleth to within approximately 1 meter depth based on typical vertical gradients.

Because measurement resolution and spatial resolution are interrelated, they cannot be specified by a single number but rather need to be quantified in terms of a curve relating the two and a relation of this curve to measurement capability. Figure 2-2 illustrates this. The ordinate is the velocity gradient spectral intensity and the abcissa, spatial frequency. The heavy black curves are theoretical curves for active turbulence† for various energy dissipation rates ϵ . The area under each curve is equal to the mean square velocity gradient, which is proportional to the

† Turbulence is synonymous with fluid velocity fluctuations. "Active" refers to fluid motion where inertial forces are larger than either buoyancy or viscous forces.

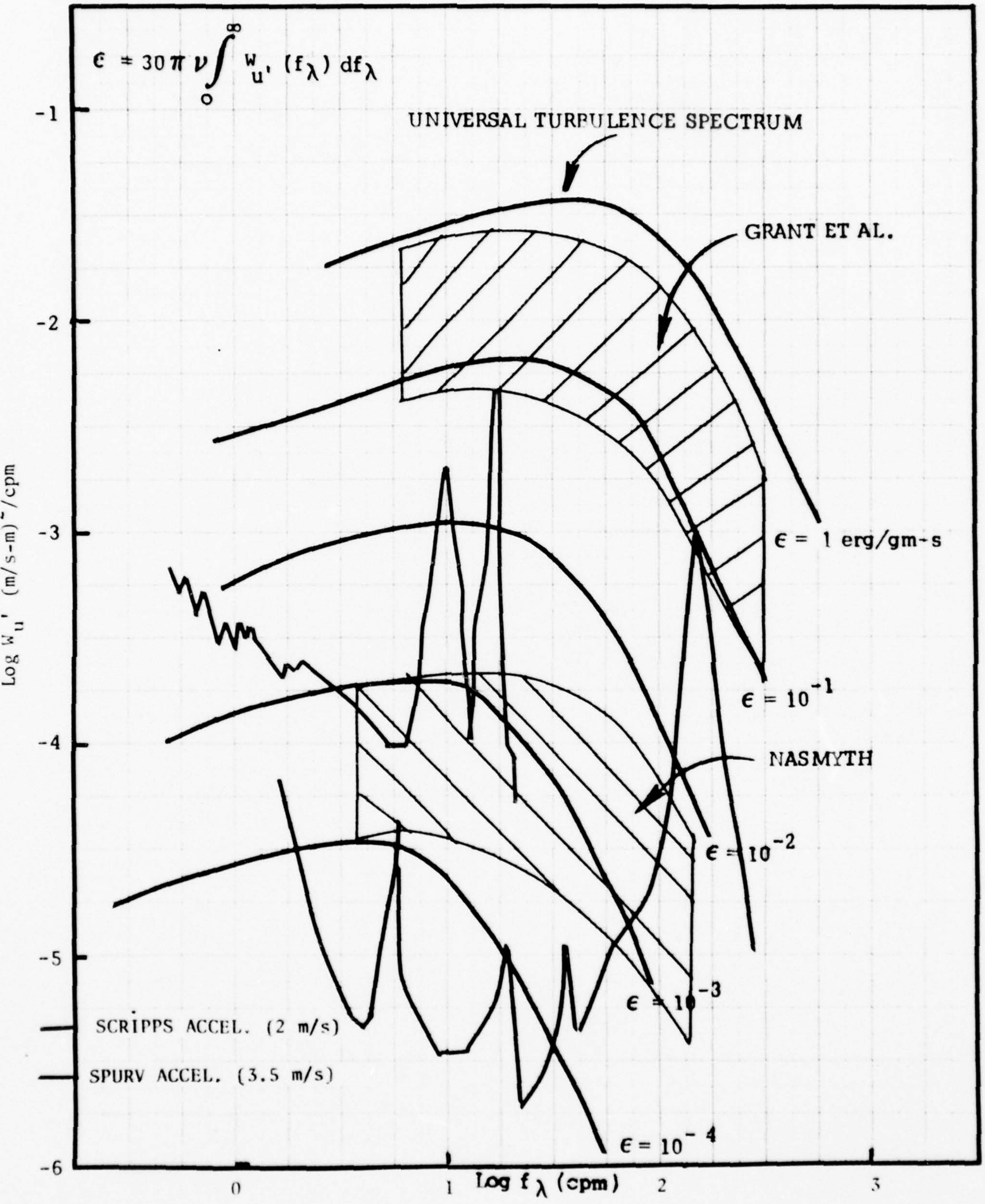


Figure 2-2. Velocity Gradient Spectra

dissipation rate ϵ, as indicated in the upper corner of the figure. The ordinate is essentially measurement resolution while the abcissa is spatial resolution. Given a certain level of ocean turbulence as specified by ϵ, which generally[1] lies between 1 and 1×10^{-4} erg/gm-s, those curves specify the measurement resolution (sometimes called sensitivity, though this actually has a different meaning) needed as a function of spatial scale. The shaded areas on the figure are envelopes of data from high and low intensity turbulent patches taken by Grant and Nasmyth, respectively[11]. The point to be made here is that relatively little data has been taken at the lower turbulence levels, mainly because of data contamination by platform motion, and consequently we cannot say what percentage of ocean turbulence levels lie below a given value of ϵ. It is thus not possible with our present level of knowledge of ocean turbulence to be able to specify a required measurement vs spatial resolution curve. As is the case in most areas of research, one uses the best sensor available in order to learn enough about the phenomena being investigated to be able to say whether or not a better sensor is needed. This is the case here. Given the performance of a particular sensor, however, the curves of Figure 2-2, and similar ones for temperature and conductivity, can be used to determine the limiting turbulence levels which the sensor is capable of measuring. Consequently, the present requirement on sensor measurement resolution and spatial resolution is that which is the state-of-the-art.

Section 3

CAPABILITIES

3.1 INSTRUMENTATION

Because of the large number of general purpose oceanographic instruments containing T, C and v sensors, it was decided to limit the instrumentation examined to that developed or used specifically for measurement of fine and microscale phenomena. As it turned out, this was necessary anyway since the measurement characteristics of the types of sensors required are highly dependent on the electronic circuitry employed. In addition, after reviewing the fine and microstructure literature and from discussions with researchers, the general concensus is that except for a few problem areas, existing sensors are by-and-large satisfactory when employed in a properly designed instrument. In view of the above, the information presented in this section consists of descriptions of several existing sensor systems and several individual sensor instruments, which give a representative picture of the state-of-the-art in fine and microscale measurement capabilities. Areas where improvement in sensor performance is desirable are discussed also.

3.1.1 Sensor Systems

When measuring the temperature, conductivity, or velocity fluctuations associated with fine and microstructure in the ocean from a moving platform, the spatial resolution of the measurement depends on the time response of the sensor as well as on its physical size. The faster the sensor response, the finer the resolution. However, the fast temperature, conductivity and velocity sensors presently available do not have very good absolute accuracy, due to calibration drift. Consequently, a second set of slower response highly accurate sensors are generally employed in conjunction with the fast sensors, and the signals from the two types of sensors are combined to yield small scale, accurate data.

Five sensor systems developed specifically for fine and microscale measurements were examined:

- APL/JHU's CUT Sensor Package
- APL/UW SPURV Instrumentation
- IOS Instrumentation
- NBIS MARK III CTD
- SCRIPPS Microscale CTD

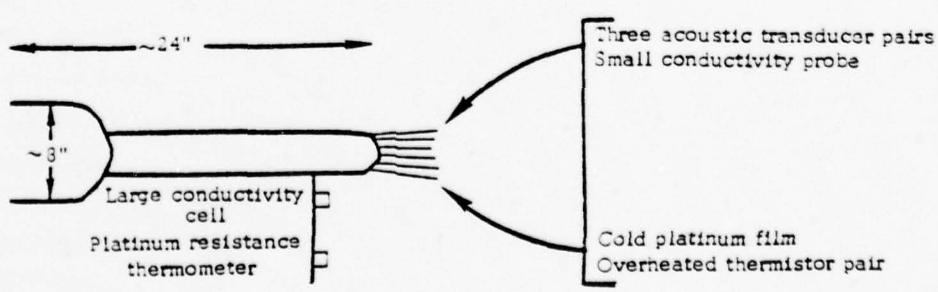
APL/JHU's Cut Sensor Package†

The Applied Physics Laboratory of Johns Hopkins University has developed a sensor package employing both a fast/high spatial resolution suite and an accurate suite of sensors for measuring conductivity, temperature and velocity.

The fast suite of sensors consist of a small, four electrode conductivity probe manufactured by Neil Brown Instrument Systems, Inc.; a TSI Inc., cold platinum film sensor for temperature; and a pair of overheated thermistors for single axis velocity.

The accurate suite of sensors consists of a larger NBIS conductivity cell, a Rosemount platinum resistance thermometer, and a triaxial acoustic velocimeter from NBIS, Inc., to measure velocity.

A rough sketch of the sensor head is shown below, and characterisitics of the sensors are listed in Table 3-1.



Rough Sketch of APL's CUT Sensor Package

† Information obtained from Dr. D. H. Johnson at APL.

Table 3-1. APL's CUT Sensor Package

SUBSYSTEM	RANGE	ACCURACY	RESOLUTION†	FREQ. RESP./ RESPONSE TIME	LIMITING SPATIAL RESOLUTION†††	STABILITY	PRINCIPLE OF OPERATION
Cold Platinum Film-Temperature	$\pm 1^{o}C$ ††	N/S	$.0002^{o}C$	50 Hz*	< 1 mm	N/S	Resistance changes with Temperatures
Small Conductivity Probe	± 1 mmho††	N/S	0.25 μmhos	50 Hz*	8 mm	N/S	Polarization impedance between voltage electrode and seawater
Overheated Thermistor Pair**	N/S	N/S	≤ 1 mm/s	50 Hz*	N/S	N/S	Differential heat dissipation
Platinum Resistance Thermometer	$\pm 32^{o}C$	$0.002^{o}C$	$0.0005^{o}C$	0.108 s	1.5 cm	N/S	Resistance changes with temperature
Large conductivity cell	1 to 52 mmhos	1 μmho	0.5 μmhos	50 Hz*	7 cm	4-5 μmhos/ month	Same as small cell
Triaxial Velocimeter	0 to 5 m/s	Greater of 1% or 0.5 cm/s	3 mm/s	50 Hz*	4 cm	N/S	Doppler shift

*Filter limited by system sampling rate.

**Still under development

† The larger of: (1) broadband noise equivalent input or (2) digitization limit.

†† Full scale change without rebalancing bride; absolute value can be set by rebalancing bridge.

††† Limited by size of sensor

APL/UW's SPURV[11,25]

SPURV (Self-Propelled Underwater Research Vehicle) has been used for about ten years by the Applied Physics Laboratory of the University of Washington to obtain accurate, continuous recordings of fine scale oceanographic data over large horizontal distances. The sensor package is modular to an extent. However, only the sensors relevant to this study are mentioned.

Accurate temperature measurements are made with a Gulton quartz crystal thermometer, while a VECO thermistor is used in a Wien bridge oscillator for faster response measurements.

Recently, a TSI hot film sensor has been added for velocity measurements, and a cold film sensor is now being used in order to extend the frequency response of temperature measurements. Details are given in Table 3-2.

IOS System[14]

The Institute of Ocean Sciences, Patricia Bay, Canada, has been making microstructure measurements with a towed system for several years and more recently, a small submersible. The instrumentation suite consists of hot and cold films, a conductivity cell, rotor current meter for mean forward velocity, a shear probe for transverse velocity (discussed below), and three acoustic flow meters. While detailed specifications were not available, they are similar to those of other similar sensors discussed in this section.

NBIS MARK III CTD†

The Neil Brown Instrument Systems Mark III CTD is a fast response, commercially available system that has been used for both horizontal and vertical profiling of small scale ocean structure for a number of years. The conductivity sensor is an 8 mm four electrode cell made from alumina ceramic with platinum electrodes. The temperature sensor is a combination of a fast response thermistor and a platinum resistance thermometer. The outputs from each sensor are processed to achieve the accuracy of the platinum resistance

† Information obtained from NBIS data sheet

Table 3-2. SPURV

SUBSYSTEM	RANGE	ACCURACY	RESOLUTION†	FREQ. RESP./ RESPONSE TIME	LIMITING SPATIAL RESOLUTION	STABILITY	PRINCIPLE OF OPERATION
Quartz Crystal Thermometer	N/S	0.01°C	0.00056°C	2 sec.*	2 cm.	.01°C/ 6 months	Resonant frequency changes with temperature
Thermistor	N/S	0.01°C	0.0004°C	80 to 100 msec	1 mm	N/S	Resistance changes with temperature
Cold platinum Film	0 to 29°C	N/S	0.001°C	100 Hz**	1 mm	2°C/yr	Resistance changes with temperature

*Sampling interval

**Electronic and sensor noise limited

† See Table 4-1

thermometer and the speed of the thermistor. Sensor characteristics are listed in Table 3-3.

Scripps Microscale CTD Package[13,14]

Scripps has developed a sensor package for microscale measurements which employs a micro-bead thermistor for temperature measurement, a heated thermistor and a small impellor current meter for velocity and a very small conductivity cell which has a spatial resolution of 3-4 mm but relatively poor long term stability. Accurate conductivity measurements determined with a larger cell are intercalibrated with those of the smaller cell. The small current meter, which has a ducted fine blade impellor, has a limiting spatial resolution of 10 cm, $\pm 1\%$ accuracy and a 2 Hz frequency response.

3.1.2 Other Sensors and Instruments

In addition to the sensor systems discussed above, a number of researchers have used other types of sensors and instruments for small scale measurements. Descriptions of some of these follow.

Airfoil Probe[8]

Osborn has modified an airfoil type velocity probe that measures velocity variations in the two components perpendicular to the probe axis. The probe tip is an axisymmetric solid of revolution. Velocity variations represent a fluctuating angle of attack of the total velocity vector thereby causing a fluctuating lift force which is sensed by two piezoceramic bimorph beams. Resolution is stated to be 1 mm/sec.

Edo Western Currentrak Doppler Current Meter

Edo Western's acoustic current meter measures biaxial velocity by transmitting two orthogonal acoustic signals and measuring the Doppler shift of the signals reflected by scatterers in the water. It has a spatial resolution of 30 cm, and its accuracy depends on the number of scatterers in the water, with a best value of 1 cm/sec.

Table 3-3. NBIS Mark III CTD

SUBSYSTEM	RANGE	ACCURACY	RESOLUTION†	FREQUENCY RESPONSE	LIMITING SPATIAL RESOLUTION	STABILITY	PRINCIPLE OF OPERATION
Conductivity	*1 to 65 mmhos*	0.005 mmhos	0.001 mmhos	50 Hz*	8 mm	$\pm$ 0.005 mmho/6 months	Polarization Impedance
Temperature	-32 to + 32°C	0.005°C	0.0005°C	50 Hz*	1 cm	$\pm$ 0.003°C/6 months	Resistance changes with temperature

*Limited by maximum sampling rate of 100 Hz

† See Table 4-1

Temperature Measurements with Conductivity Probes

In ocean areas where conductivity is dominated by temperature and not salinity, it is possible to use conductivity cells to sense temperature fluctuations. The advantages to this are that conductivity cells are more rugged than platinum film or thermistor probes and they have a much higher frequency response. Gibson[13,20] has used the Scripps microconductivity probe for such measurements.

Acoustic Vorticity Meter[12]

An acoustic vorticity meter has been under development by Triadic Research, Inc., to detect oceanic vorticity with sensitivity comparable to the vorticity of ambient internal waves. Circulation is estimated by the average time difference for sound to be reflected in opposite directions around a vertical twenty centimeter triangular closed path, giving the mean horizontal vorticity component perpendicular to the tow direction.

Vorticity is a direct result of current shear, turbulence and internal waves. If it is possible to separate internal waves and current shear from the signal, this instrument has good potential for measuring turbulence to scales of about fifteen centimeters with several orders of magnitude improvement in signal to noise compared to heated element sensors.

Cal Tech LDV

Dr. John List at the California Institute of Technology has been developing a three axis Laser Doppler Velocimeter for underwater velocity measurements from a towed platform†. While the instrument has been used in the laboratory, the underwater system is still in the early stages of development. Its development should be monitored by NORDA since the LDV could eliminate a number of the operational problems associated with hot film sensors although it does have unique problems of its own.

---

† Personal communication.

3.1.3 Problem Areas

The major problem area in sensor capability is the limitation on scale size due to limited sensor frequency response. The limiting scale size can be seen to be

$$\lambda_{min}\ (\text{cm}) \simeq \frac{50}{f_{max}\ (\text{Hz})} \times V_{platform}\ (\text{kts})$$

where $V_{platform}$ is the sensor platform speed. In order to measure down to a scale of 1 cm, the frequency response f_{max} required ranges from 100 Hz to 400-600 Hz over the towed body speed range of 2 to 8-12 knots. While it is not apparent from the frequency response of the instruments discussed above, most of which are sampling rate-limited and not sensor-limited, conductivity and heated-film velocity sensors can meet this requirement. Temperature sensors, however, have a response limited by thermal inertia with a typical 3 dB rolloff around 10 Hz for thermistors and 50 Hz for thin film sensors. While this response can be calibrated and compensated for, electronic and sensor noise have thus far limited the useful maximum to 100-200 Hz. Consequently, platform speeds are necessarily limited to 2-4 knots if a 1 cm spatial resolution of temperature microstructure is desired. Although one cannot specify a single hard and fast number for the required spatial resolution, the considerations of Reference 13 indicate a need for a resolution on the order of one centimeter.

Other problems, not directly related to measurement capability but which can nevertheless influence measurement quality are: (1) fouling of thermistor and thin-film probes affecting both temperature and velocity measurements and (2) contamination of heated film/thermistor velocity data due to sensitivity to temperature fluctuations. The former problem can be solved by washing the probes periodically with a water jet[14]. Data is interrupted for a few seconds during the wash but this is generally acceptable. The second problem can be eliminated, at least in principle, by employing two

probes with different overheats which makes it possible to separate velocity from temperature fluctuations[13]. The success of this technique is unknown as it has not yet been tried in practice.

In summary, existing sensors employing properly designed electronics are by-and-large adequate for fine and microscale measurements of T, C and v from a slow moving platform. The major problem, which is presently the one of greatest concern in the microstructure community, is the contamination of velocity data due to towed body and resultant sensor vibrations[14]. This will be discussed in the following subsection.

3.2 TOWED BODIES

A similar approach to that of the instrumentation was taken in examining potential candidate towed body systems. Because of the large number of towed systems in existence, it was decided to limit the scope to those which were designed and/or used specifically for towed oceanographic measurements, provided there were a sufficient number of such towed body systems in existence. This, in fact, turned out to be the case.

Towed body oceanographic measurement systems examined for this study included:

- Guildline Instruments Batfish
- MIT Towed Instrument Glider
- WHOI Two Body Towed System
- Institute of Ocean Sciences System
- Scripps Towed Ocean Profiling System
- APL/JHU Towed Ocean Profiling System
- NAVOCEANO Developmental Towed Body
- University of California, Berkeley, Towed Vehicle

In addition to these, other improvised towed systems that came to our attention were examined in order to ensure that none of importance were overlooked. Although not a towed body, APL/University of Washington's SPURV (Self Propelled Underwater Research Vehicle) was included in the study since it has been used for finestructure measurements and represents the limiting case of a towed system with no surface ship motion coupling or tow cable vibrations. The following subsections give a brief description of each of the above towed measurement systems. Additional information can be found in the Appendix.

Batfish[14,15]

Figure 3-1 shows the Batfish, originally developed by the Bedford Institute of Oceanography and now manufactured by Guildline Instruments. The Batfish has a depth capability of 400 m at speeds of 5-9 knots with 600 m of faired cable deployed. It can be commanded to fly a predetermined profile or to maintain a constant depth. The depth keeping capability in the constant depth mode is quoted as being "within 1 m in most cases" although no mention is made of ship tow point motion dependence.

A fair amount of data has been collected on linear and angular motions of the Batfish during various depth maneuvers and is contained in the Appendix. This data indicates that pitch and roll motions as well as relatively high vibration levels in the range 4-50 Hz, preclude the use of fine and microscale velocity sensors. Additionally, because it is a direct coupled system with no ship motion decoupling other than the tow cable catenary, it will only be suitable for limited fine and microscale temperature and conductivity measurements in low sea states.

MIT Glider[14,16]

Figure 3-2 is an overall view of the Massachusetts Institute of Technology, Department of Meteorology, Towed Instrument Glider. The glider was built as a prototype for meteorology studies in near surface waters. It

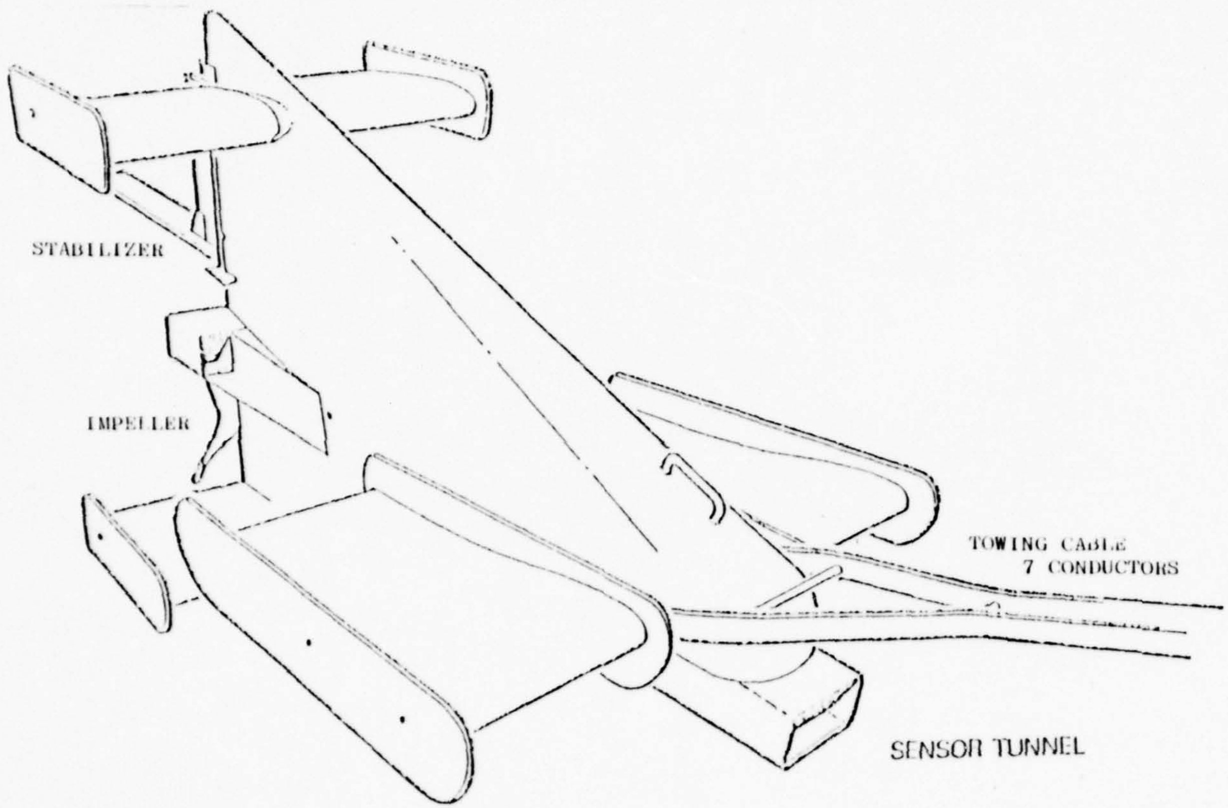


Figure 3-1. Batfish

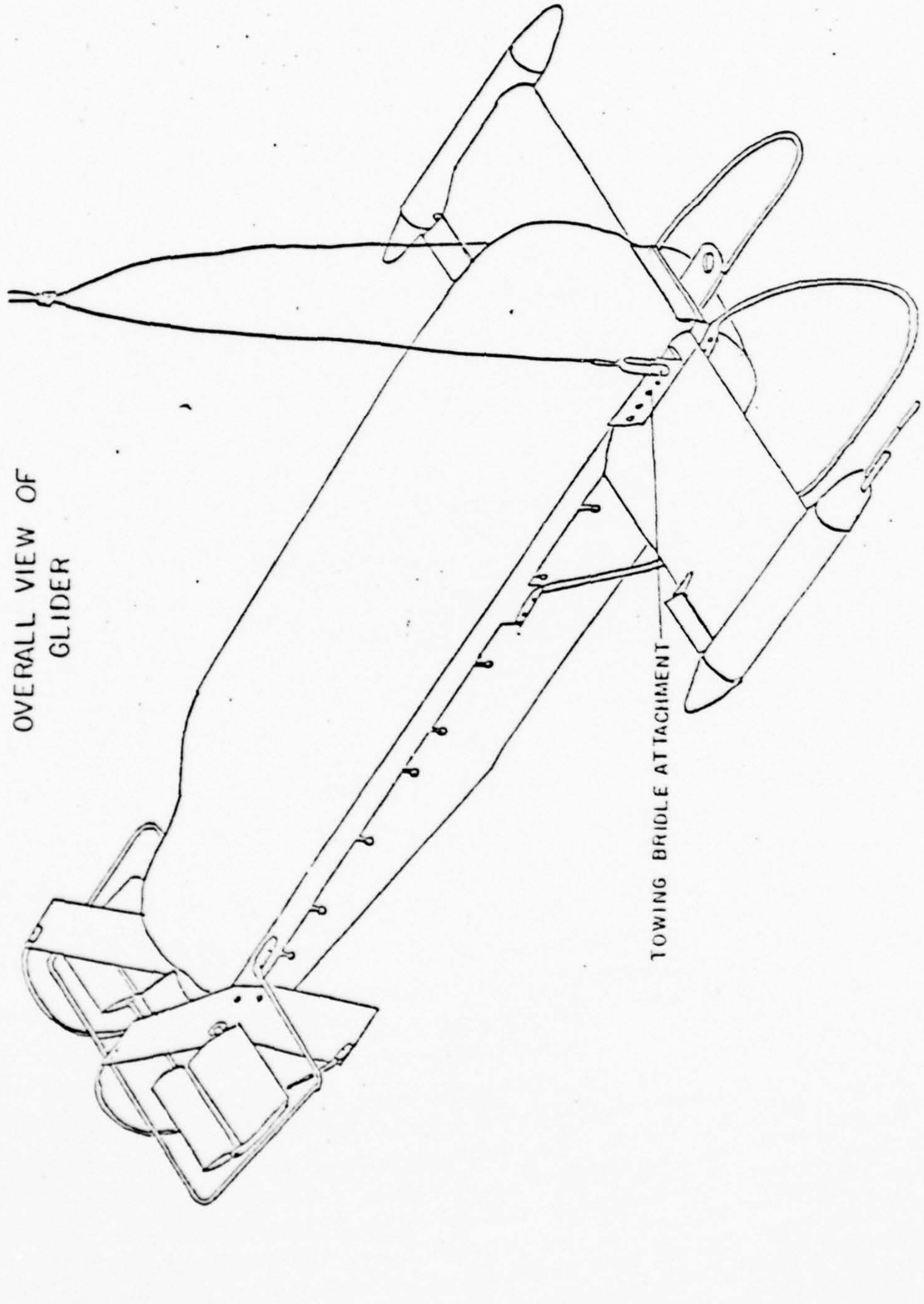


Figure 3-2. MIT Glider

has been successfully tested in the depth range 0 to 30 m at speeds from 4 to 10 knots. While it could conceivably be used at greater depths, its non-streamlined design is prone to body structural vibrations generated by flow, precluding its use with sensitive, small scale velocity sensors. Additional information on the glider is contained in the Appendix.

WHOI Two Body Towed System[14,17]

The Woods Hole Oceanographic Institute has developed a towed system employing two bodies, an upper one primarily for depth control and a second one, towed behind and below the first, carrying the principal sensors. Depth penetration is achieved solely by the weight of the tow cable and the two bodies, although enough lift can be generated by the depth control body to vary the depth up to 200 m at a tow speed of 6 knots. Design speed is 4 to 8 knots and depth capability is limited only by the length of the tow cable available and the crush depth of the body of approximately 4000 m.

The major design goal of the system was to minimize cable tension and the resultant cable fatigue and vibration in order to eliminate the need for expensive fairing and to maximize system reliability. An additional benefit of low cable tension and the resultant large cable scope to depth ratio, about 7 to 1 at 6 knots for this system, is significant decoupling from ship motion. This, however, also makes the system more sensitive to changes in the current from surface to tow depth, resulting in times when steady depth control has been difficult.

While the WHOI system was not designed for making small scale measurements, the two body concept, in addition to providing the convenience of interchangeable sensor bodies, is one which could be quite useful in providing additional decoupling of any ship motions transmitted to the first body as well as decoupling from vibrations in the main tow cable. This is discussed further in Section 4.

Figures 3-3 and 3-4 show the depth control body and three different sensor fish. The ring tail on the depth control body can be rotated to vary the lift and is driven by a hydraulic system powered by the impellor within the ringtail. More detailed information is contained in the Appendix.

Institute of Ocean Sciences System[14]

The Institute of Ocean Sciences has been involved in fine and microstructure measurements since the early 1970's using first a towed system and more recently a manned submersible Pisces IV. The towed system was initially developed and used in the 1960's by Grant and others at the Pacific Naval Laboratory (now the Defense Research Establishment Pacific) at Esquimalt, British Columbia. This towed system, depicted in Figure 3-5 has probably collected more towed fine and microstructure data than any other in existence . The body is approximately 80 cm in diameter, 370 cm long and weighs about 1000 kg. Depth control and ship motion decoupling are maintained by a motion compensating winch which can be programmed to maintain a constant depth or to cycle over a sawtooth path at climb/dive amgles of 20°-40°. Depth can be maintained to within $\pm$ 0.5 m in sea states up to 5. Maximum depth, limited by available cable length is 350 m at the average towing speed of 3 knots, which was chosen as a compromise between sensitivity of the velocity probes and the ability to control the ship in winds up to about 30 knots. A faired tow cable (lower 100 meters) and a vibration isolation mount are employed to minimize contamination of velocity data.

Although this system was shelved in 1974, when the IOS group began using Pisces IV, it was, and still is, the most capable, proven towed system available for fine and microstructure measurements. Its depth keeping capability, according to discussions with Dr. P.W. Nasmyth, the head of the IOS group, is quite satisfactory for measurement of temperature and conductivity data. Velocity data, however, in all but the calmest seas, suffers from sensor motion contamination due primarily to residual ship motion coupling, which has the greatest effect at the fine structure scales. The IOS group was considered adding

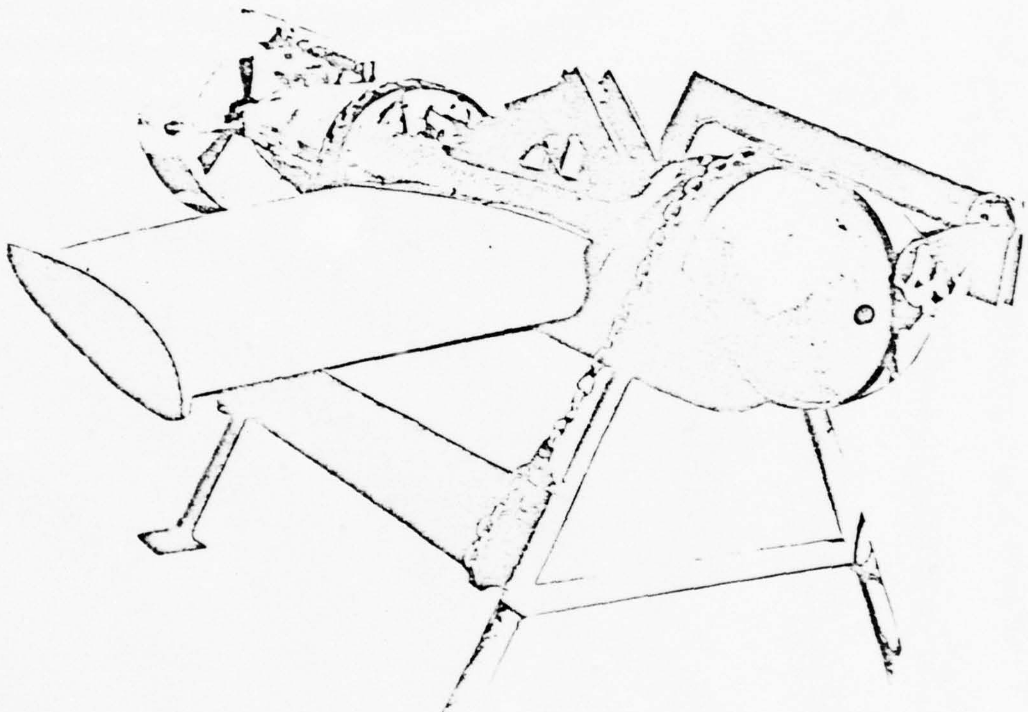
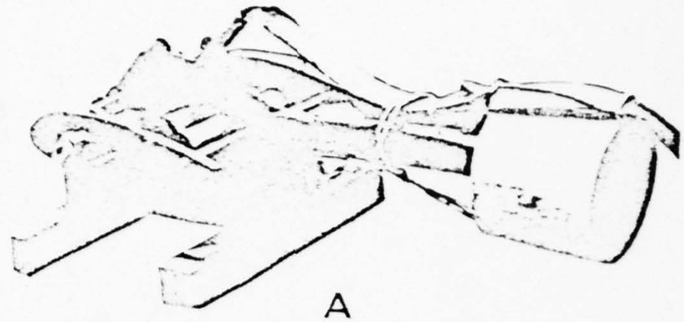
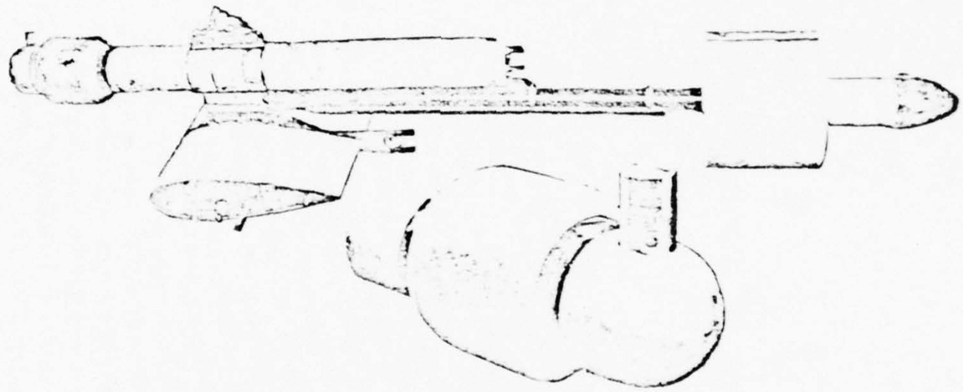


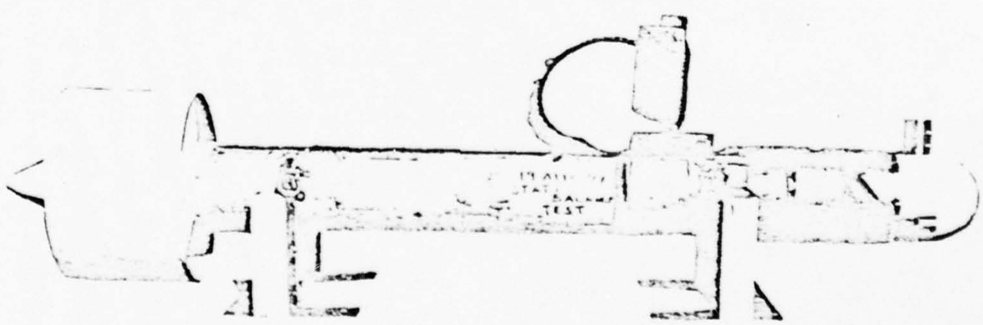
Figure 3-3. WHOI Depth Control Body. Shown resting upside-down and the belly cover removed. The 2.3 m long fiberglass body is towed from the forward tow bar, which is free to rotate in the vertical plane through the nose cone. The second tow bar aft is for the sensor fish.



A



B



C

Figure 3-4. WHOI Sensor Fish. (A) Fish consists of 3 Plessey CTD sensors and a pressure cased signal mixer simply shrouded in the wings (shown uncovered). A later version with an enlarged wing, successfully towed a Beckman dissolved oxygen sensor as well. (B) In addition to the Plessey CTD, a Doppler scattering current meter is mounted in the nose (see insert) and a flux gate compass in the tail. The fuselage is a pressure casing containing all the electronics and a two-axis tilt sensor. (C) The latest version has the Plessey CTD sensors replaced by the NBIS sensors seen protruding from the side of the nose.

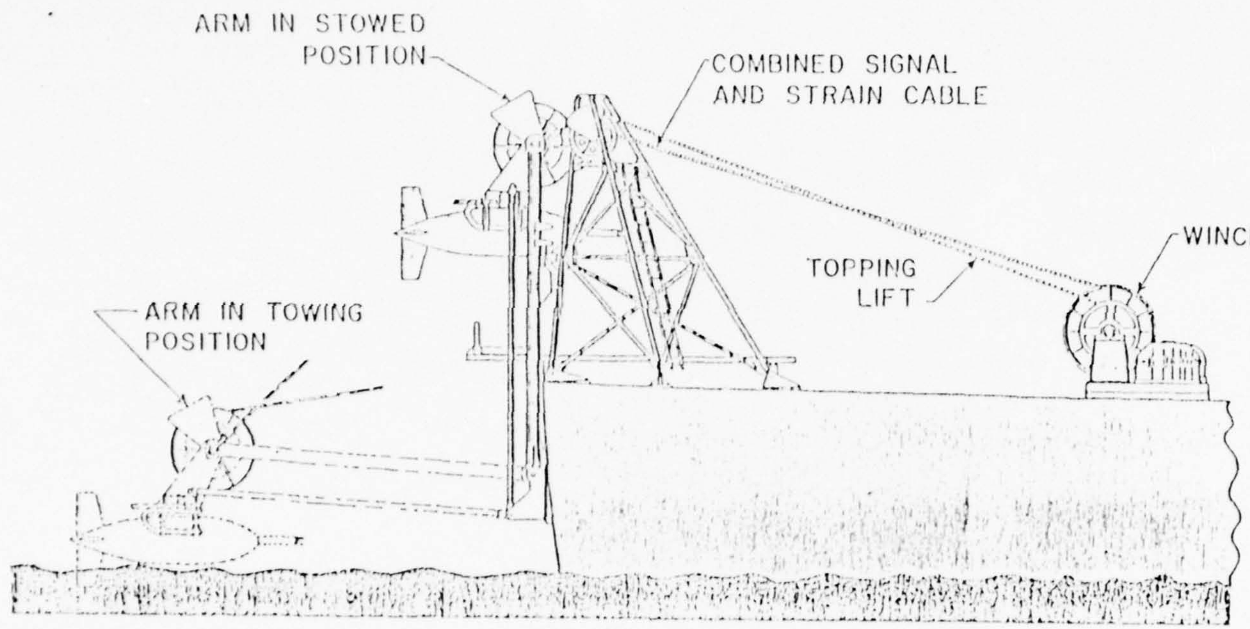


Figure 3-5. IOS System

a second body, as in the WHOI system, for additional low frequency decoupling at the time they discontinued use of the towed system. Additional information on this system may be found in the Appendix.

Scripps Towed Ocean Profiling System[14,18]

A recent addition to towed oceanographic measurement systems is depicted in Figure 3-6. This system employs a catamaran body which rides freely up and down a near vertical support cable on a sheave near its center of mass. While the figure shows two depressors on the support cable, the system has been used, and performs quite satisfactorily with one depressor at the lower end of the cable. The faired tether cables, which are neutrally buoyant, carry power and data and act as hydroelastic springs which decouple the vertical motions of the support cable and depressor from the body. The body can "fly" up and down between the tether cable attachment points by use of the elevator control. The body itself weighs approximately 50 lbs in air, is neutrally buoyant in water but has a virtual mass of 370 lbs due to a large free flooded volume. The design of the body/tether system was optimized by a stability analysis performed by the Naval Coastal Systems Center[19].

The Scripps system, which was developed under funding from APL/JHU, has been tested only under limited sea state conditions but appears to decouple vertical cable motions quite well and maintain depth to within less than 1 m, which means that it should at least be useful for fine and microscale measurements of temperature and conductivity. The Scripps system was in fact used during the MILE experiment to collect such data at tow speeds of 3-5 knots and depths to 60 m[20]. Body accelerations up to frequencies of 50 Hz measured during the experiment are shown as the red curve in Figure 2-2. These levels are relatively high and its suitability for velocity measurements remains to be determined based on additional testing and techniques which can be employed to reduce and/or

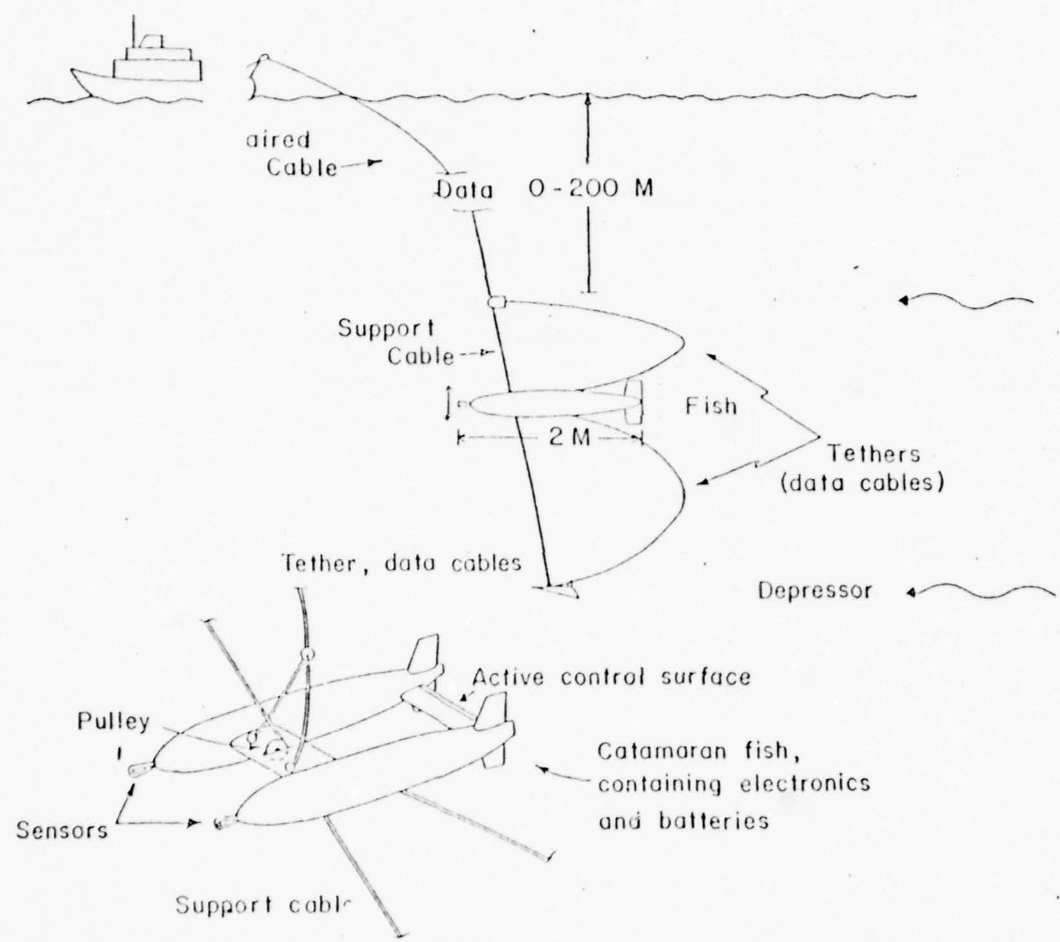


Figure 3-6. Scripps Towed Ocean Profiling System

compensate for body/sensor vibrations. Additional information on system characteristics as well as some body motion data can be found in the Appendix.

APL/JHU Towed Ocean Profiling System[21,22]

The APL/JHU system is basically the same as the Scripps system, the main differences being: (1) a smaller tail flap, (2) the addition of a flap on the main wing to permit lift changes without pitch changes, (3) the use of longer tethers for increased profiling capability and (4) the use of a more sophisticated flap drive mechanism. Recent sea tests of the APL system have confirmed the success of these modifications, although the tether cables employed were much larger than necessary resulting in degraded decoupling of the depressor and body motions. Even so, data from depth sensors on both the depressor and body indicate a decoupling capability of at least 5 to 1. This should increase considerably with the use of smaller diameter tethers which will be employed in a future sea test. Data on vibration levels were not available at the writing of this report but it is anticipated that they will be of similar magnitude to those of the Scripps system. APL plans to investigate the use of a "soft" attachment between the sheave and body as a means of reducing the effect of cable vibrations. The Appendix contains some additional information on the APL system. Data from APL's recent at-sea test was not available for publication at the writing of this report.

NAVOCEANO Developmental Towed Body[23]

NAVOCEANO has under development a towed body system to be used for conductivity and temperature measurements in the upper ocean. The body, shown in Figure 3-7, is a bi-wing, high lift body which is a modified version of a mine-sweeping depressor developed by NSRDC. It incorporates a vertical tail flap actuated by a pendulum for roll stabilization and an elevator which can be operated in an open loop or a closed loop mode for constant depth operation. It will carry a Neil Brown Instrument

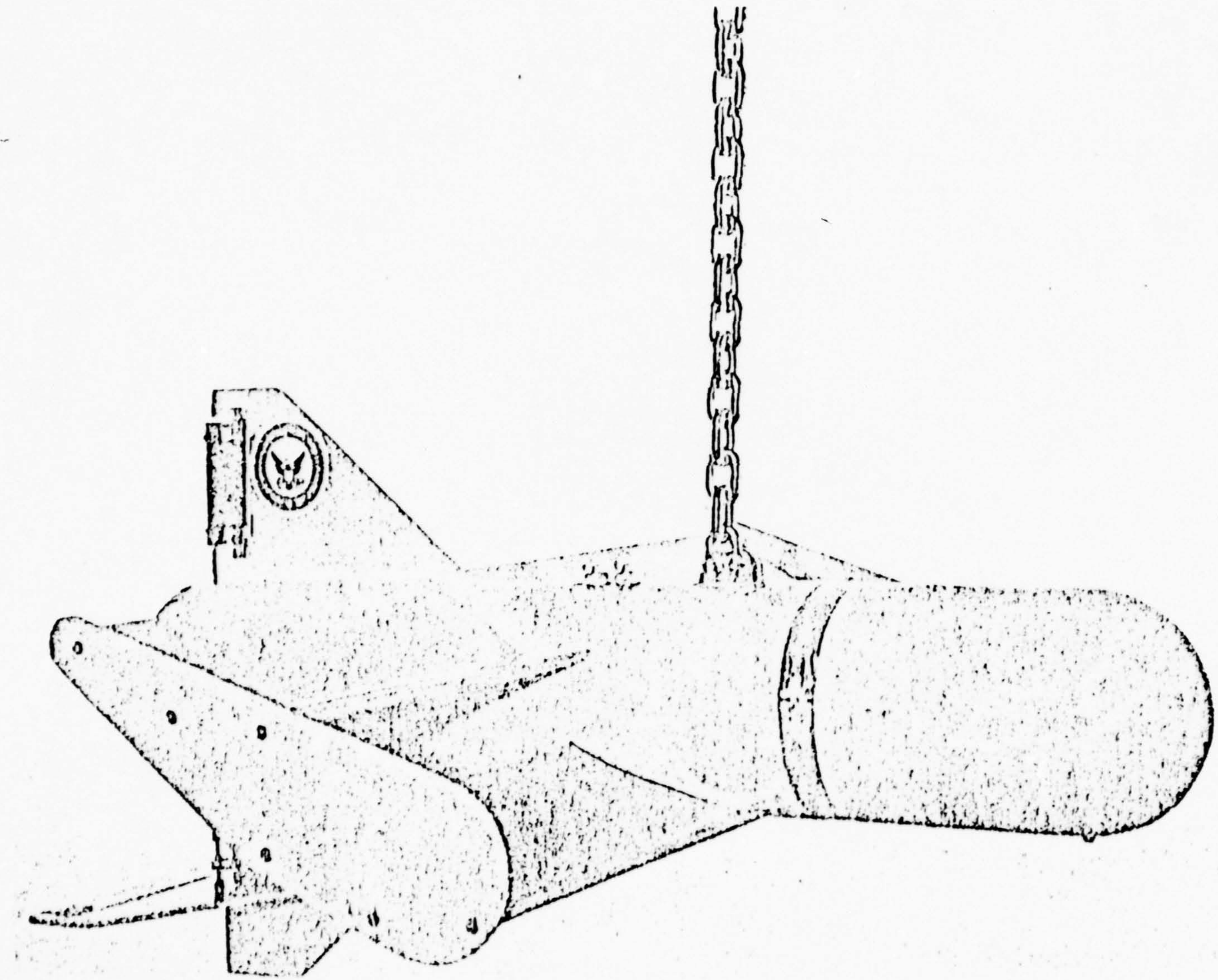


Figure 3-7. NAVOCEANO Towed Body

Systems CTD and will weigh approximately 96 pounds in air. The body is approximately 67" long and 7" in diameter with a 51" wingspan and 24" vertical tail. Tank tests have been performed by NSRDC to verify acceptable towing characteristics and at-sea testing is planned for this fall. No data exists as yet on the depth keeping capability or the acceleration levels of this body since the modified version has never been to sea. Additional information on the physical and electrical characteristics of the system can be found in Reference 23.

UCB Towed Vehicle[24]

The University of California at Berkeley has developed a towed vehicle capable of constant depth and bottom contouring operation for pollution monitoring studies in estuarine and marine environments. A schematic of the vehicle is shown in Figure 3-8. Depth and speed ranges are 0-30 m and 1-4 knots, respectively. Construction is plexiglass and fiberglass reinforced polyester. The vehicle is towed with a 1/4" polypropylene rope and consequently all data, which consists of temperature, conductivity, dissolved O_2, pH, turbidity, and pressure measurements, are recorded on board the body. This system is really not suitable for NORDA's application but was included for the sake of completeness. Additional information on this system may be found in Reference 24.

APL/UW SPURV[11,25]

APL/University of Washington's Self Propelled Underwater Research Vehicle has been under development since 1963 as a stable platform for oceanographic sensors. Low frequency temperature and conductivity sensors as well as a fluorometer have been used on the original version designated SPURV I. An improved version, SPURV II, is presently being evaluated by APL/UW as a platform for high frequency temperature and velocity sensors for measurement of fine and microscale phenomena. In addition to having a wider speed range than SPURV I, 4 to at least 7 knots as opposed to 4 to 5 knots, SPURV II contains a 3-axis accelerometer package near the

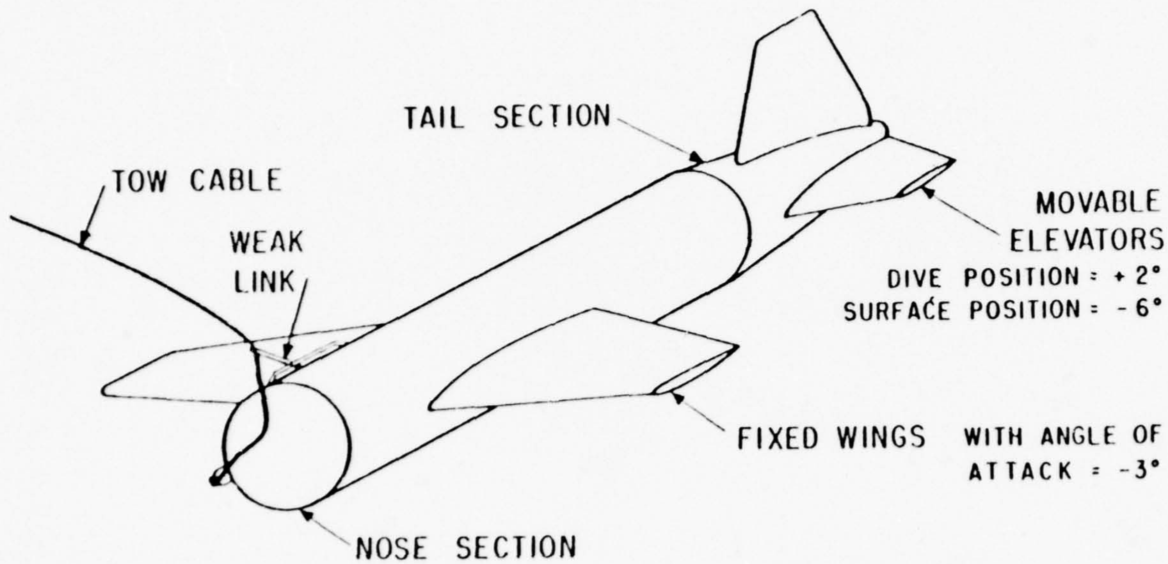


Figure 3-8. UCB Towed Vehicle

sensors to monitor vibration levels. Figure 3-9 shows a schematic of SPURV II.

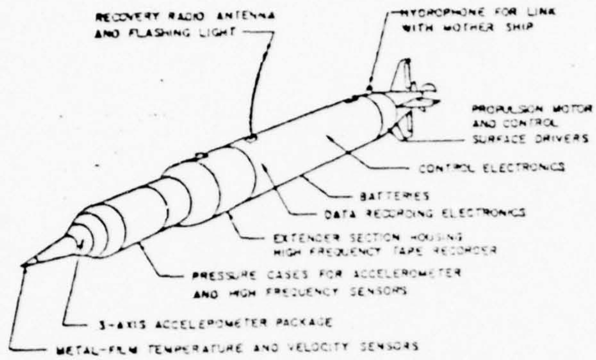


Figure 3-9. The SPURV II Vehicle

The purpose of including SPURV in this study was for use as a baseline for platform motion levels. Since there is no tow cable, ship motions and tow cable vibrations are absent and one is left with motions due only to the natural stability of the vehicle and from natural and motor induced structural vibrations. From the blue curve of Figure 2-2, it can be seen that vibration levels are quite low except for the large peak just above 100 cycles/m, which is related to the motor speed. At lower speeds, these levels become even lower. Although no data was available on depth stability for SPURV II, SPURV I depth control could be maintained to within less than 10 cm and it is expected that SPURV II stability is similar. If ship motion and cable vibration can be sufficiently decoupled from a towed body system, then one would expect to be able to do at least as well as SPURV's performance.

Other Systems

While it is impossible to be certain that no other towed oceanographic measurement systems were overlooked in this study, it is highly unlikely that any of potential use for operational fine and microscale measurements were missed. The microstructure community as well as the

towed body measurement community are relatively small, close knit groups that are aware of each other's work. Since we talked with a number of prominent researchers in each of these communities, it is unlikely that we have left out any significant instrumentation or towed body systems that are being used for the collection of oceanographic data in the upper ocean.

Section 4

EVALUATION

The present section compares the results of the previous two sections in order to determine which instrumentation and towed systems meet NORDA's requirements for towed fine and microscale measurements. Section 4.1 discusses instrumentation in terms of a recommended baseline suite and a recommended optional sensor suite. Section 4.2 discusses existing towed body systems in terms of the degree to which they meet the requirements of Section 2. Additional capabilities gained by combinations and/or modifications of existing systems are also discussed. While at least one existing system meets the requirements for temperature and conductivity measurements, none presently meet or appear likely to be capable of meeting the body motion levels needed for measurement of velocity at the lower intensity levels. Consequently, Section 4.3 discusses and ranks alternative concepts for a system capable of measuring v in addition to T and C.

4.1 INSTRUMENTATION

4.1.1 Recommended Baseline Suite

Section 2, Requirements, stated that T, C and v sensors should meet the range and accuracy requirements specified in Table 2-3 and that the measurement and spatial resolution should be state-of-the-art since not enough is presently known about the distribution in the ocean of the various fluctuation intensity levels to be able to specify a required measurement resolution vs spatial resolution curve. Based on this and on the sensor capabilities discussed in Section 3, the baseline instrumentation suite recommended is given in Table 4-1. As discussed in Section 2, both a fast and a slower but accurate sensor are specified for each parameter in order to maintain accuracy over the entire frequency range. With regard to fast T and v, platinum film probes have been recommended over thermistors because of the slower drop off in frequency response. A good discussion

Table 4-1. Recommended Baseline Instrumentation Suite

PARAMETER		SENSOR
FAST	T	Dual heated, constant temperature platinum film probes
ACCURATE	T	Platinum resistance thermometer
FAST	C	Microconductivity probe
ACCURATE	C	Conductivity cell
FAST	$v_{\parallel}$	Dual platinum film probes
FAST	$v_{\perp}$	Shear probe
ACCURATE	v	Triaxial acoustic phase shift Velocimeter
SENSOR MOTION		Accurate depth transducer plus triaxial accelerometer near sensors

of the pros and cons of both platinum film and thermistor sensors are contained in References 13 and 14.

In addition to the oceanographic sensors, a knowledge of sensor motion is mandatory in order to place confidence levels on data collected. An accurate depth transducer is needed to determine contamination of T and C data and a triaxial accelerometer near the sensors is needed to determine vibration levels which contaminate velocity data.

4.1.2 Optional Desirable Instrumentation

In addition to the baseline suite recommended above, the following sensors would provide additional valuable information.

High Frequency Fathometer

An HF fathometer, probably pointed upward from the towed body, would measure motion of scattering layers due to internal waves. Besides the additional capability of 2-dimensional mapping of the internal wave field, this would aid in isopycnal surface following and in determining contamination of constant depth tow T and C data due to the vertical motion of the vertical finestructure caused by internal waves[4]. APL/JHU has made such HF fathometer measurements from a port in the bottom of a ship and more recently, Woods Hole, from a shallow towed body. In both cases, the feasibility of such measurements was confirmed but problems were experienced due to angular motions of the platform. A towed body with good angular stability, instrumented with pitch and roll sensors, is a pre-requisite for use of this instrument.

T and C Sensors Along Tow Cable

The addition of temperature and conductivity sensors along the tow cable provides simultaneous data at more than one depth, which, in addition to increasing the overall data collection rate, allows the measurement of vertical correlations which can be difficult to measure

with a single point sensor on a towed body. The vertical correlation length, as discussed in Section 2, determines the towed body depth stability required to prevent contamination of horizontal tow data by the vertical structure. In addition, vertical motions of the pycnocline due to internal waves are easier to interpret from simultaneous data at several different depths. Because of cable vibrations, the use of velocity sensors along the tow cable other than to measure mean current shear, would not be practical.

Acoustic Vorticity Meter

Because vorticity is not affected by linear motion, including linear vibrations, it is theoretically a more sensitive indicator of turbulence than linear velocity since platform angular vibrations are generally considerably less than linear vibrations, especially at the higher frequencies. While internal waves and current shear also produce vorticity, the spectral characteristics of the three processes are expected to be different enough that they can be distinguished from one another. In fact, the measurement of vorticity may be one of the best methods of separating these various phenomena when all three are present simultaneously. While the acoustic vorticity meter is presently still under development, it should be considered as a potentially valuable addition to a towed fine and microscale measurement system.

4.2 TOWED BODY SYSTEMS

4.2.1 Existing Systems

The towed body systems discussed in Section 3 were given an initial evaluation based on depth range, speed range and overall controllability. Three of these, the WHOI, MIT and UCB systems were judged unsuitable in at least one of these areas. This is not to say that these systems are not suitable for the application for which they were intended but only for the fine and microscale measurement application.

The remaining five systems were judged to be candidates and were subjected to a more detailed evaluation to the extent possible based on available data on body motion levels, discussed in Section 3 and the Appendix. Table 4-2 summarizes the results of the eight towed systems considered. The NAVOCEANO towed system is presently undergoing evaluation and data is not available at this time but it is anticipated that it will be suitable for at least fine and microscale T and C measurements, although under limited sea state conditions due to the fact that it is a direct coupled system with no special ship motion decoupling mechanism.

The Batfish is also suitable for only limited T and C measurements because of the direct coupling. It is unsuitable for velocity measurements because of the high vibration levels and the, at best, fair pitch and roll stability. This is not to say that the Batfish could not be suitably modified, but as it now exists it is unsuitable for fine and microscale velocity measurements.

The IOS towed system is definitely suitable for fine and microscale measurements of T and C in sea states up to 5, based on extensive at-sea experience. The Scripps and APL systems appear to be suitable for T and C measurements although only limited at-sea data is available. All are of limited suitability for velocity measurements, that is, limited by body acceleration levels. From the Scripps accelerometer data of Figure 2-2, it appears from the frequency range covered of 1-50 Hz that accelerations due to ship motion coupling, cable vibrations and body structural vibrations may all be present. While no published data is available on IOS acceleration spectra, the major source of motion contamination of velocity data, as mentioned in Section 3 is the residual ship motion coupling in the frequency range 0.2-1 Hz which cannot be sufficiently removed by the sensor vibration isolation mount which has a natural frequency of 1-2 Hz[14]. Consequently, contamination is a problem in the scale range of approximately 0.5-7.5 m, the lower end of the fine scale region.

Table 4-2. Existing Towed System Evaluation Summary

SYSTEM	INITIAL EVALUATION	DETAILED EVALUATION	REMARKS
IOS	Candidate	FS T, C, limited v μS T, C, v	Extensive measurements by Canadians; presently shelved
Scripps and APL/JHU	Candidate	FS T, C limited v μS T, C limited v	Designed specifically for fine and microscale measurements; limited at-sea experience
BATFISH	Candidate	Limited FS T, C Limited μS T, C	Direct coupled; high inherent vibration levels; fair to poor angular stability
NAVOCEANO	Candidate	Undergoing Evaluation	Anticipate at least limited FS and μS T and C
WHOI	Unsuitable		Very slow climb (10 m/min); poor speed and position control due to extreme cable scope
MIT GLIDER	Unsuitable		Designed for 0-30 m depth
UCB	Unsuitable		Designed for 0-30 m depth

In summary, there are three existing systems, the IOS, APL and Scripps systems, which are or appear to be, from presently available data, capable of meeting the requirements for fine and microscale measurements of temperature and conductivity. None of these systems are adequate for velocity measurements over both the fine and microscale ranges at the lower intensity levels (down to $\epsilon = 10^{-4}$ erg/gm-s) The IOS system, however, appears to be suitable for microscale velocity measurements up to sea states of 5 but is only suitable for finescale velocity measurements at the lowest sea states. A quantitative estimate of this "suitability" is unfortunately not possible since no data has been published on sensor motion spectra. Since velocity measurements are crucial to a scientific understanding of the generation and dissipation of fine and microscale phenomena in the ocean, the conclusion is that no system presently exists which is entirely adequate for NORDA's purposes. The following subsection discusses several modifications of these existing systems which can be expected to improve their velocity measurement performance.

4.2.2 Modification of Existing Systems

Table 4-3 lists four modifications to the APL, Scripps and IOS systems, the advantages and disadvantages of each, and the velocity scales over which measurement capability will be improved. The first and third items are employed in the existing IOS system and the second item was under consideration by the IOS group to increase the decoupling from ship motion beyond that supplied by the motion compensating winch, which is on the order of 10 to 1. The addition of a motion compensating winch also allows the use of temperature and conductivity sensors along the tow cable for fine and microscale measurements. Unfortunately, due to lack of data, it is difficult to make a quantitative estimate of the degree of improvement afforded by each of these modifications. The following subsection, however, makes a semiquantitative comparison of several conceptual systems, including the modifications of Table 4-3, based on the various approaches which have been or can be taken to solve the sensor motion contamination problem.

Table 4-3. Modifications of Existing Systems

Modification	Applicable System		Advantages	Measurement Improvement	Disadvantages
	APL/ Scripps	IOS			
Add motion compensating winch	X		Increased ship motion decoupling	FS velocity	Increased cost; requires dedicated ship
			T, C sensors can be added along tow cable	Increased information	
Tow secondary sensor body from towed body	X	X	Increased ship motion decoupling	FS velocity	Increased complexity; no performance data available
			Decoupling from cable vibrations and depressor structural vibrations	μS velocity	
Put sensors on vibration isolation mount	X		Decoupling from cable vibrations and depressor structural vibrations	μS velocity	Increased complexity
Compensate data electronically using simultaneous accelerometer data	X	X	Less stringent allowable motion levels	μS and FS velocity	Uncertainty in degree of effectiveness

4.2.3 Conceptual System Evaluation

Based on the examination of existing towed body systems and the difficulties encountered in their use, the critical problems in fine and microstructure measurement from a towed body can be stated to be:

- Ship motions transmitted to the towed body
- Tow cable vibrations transmitted to the body
- Body structural vibrations due to hydrodynamic flow

The first problem affects measurements of all parameters (T, C and v) while the latter two are important only for velocity measurements, (neglecting vibration effects on poor electrical connections). There are two general types of approaches which may be taken to solve these problems which we will call the "physical" and the "electronic" approach. The physical approach is to attempt to isolate the motions before they reach the sensor. The electronic approach is to compensate electronically for sensor motion using simultaneous data from accelerometers or other motion instrumentation. These two approaches are discussed separately in the following.

Physical Approach Evaluation

Table 4-4 lists the above problems along with physical techniques available to solve them. The cable rider body is the Scripps/APL type system while the depressor towed body refers to a two-body system such the WHOI system. Any scheme for evaluating alternative systems should include an evaluation of the systems' ability to eliminate these sources of motion. The scheme we have used to evaluate the conceptual systems presented below, is based on the following criteria:

Table 4-4. Critical Problems and Physical Solution Techniques in Fine and Microstructure Measurement from a Towed Body

Ship Motions transmitted to body (T, C, v)

- At Ship: Motion compensating winch
- At body: Cable rider (CR) or depressor towed (DT) body

Cable vibrations transmitted to body (v)

- Fairing to decrease vibrations
- "Soft" attachment (CR and DT only)
- Sensor vibration isolation mount

Body structural vibrations (v)

- Sensor vibration isolation mount

- Degree of ship motion decoupling
- Degree of cable vibration decoupling
- Overall system simplicity
- Handling ease
- Tow cable tension variation
- Volume and weight
- Risk
- Cost

Body/sensor motion decoupling (via a sensor isolation mount) was omitted from the criteria because it is basically an add-on with similar performance for each system. While one can think of additional criteria, we feel that these are the most important.

The actual conceptual systems are based on the three system factors and the alternatives for each factor shown in Table 4-5. The instrument body is defined as that which carries the instruments, and the depressor as that which serves only (or primarily) to depress the tow cable. For a single body system, such as the IOS system, the Depressor Control factors are to be ignored. Active control means moveable lifting surfaces. Table 4-6 is a listing and evaluation of conceptual systems resulting from practical combinations of factors in Table 4-5. In addition, a motion compensating winch (MCW) augmenting the cable rider instrument platform (CRIP) and the depressor towed instrument platform (DTIP) is considered. Because of its complexity, a secondary body towed from a CRIP system (CRIP/DTIP combination) was not considered. The first two concepts labeled simply MCW imply a single body system such as the IOS system. The fourth column notes that three of the candidate concepts already exist.

The evaluation was done as follows: the various system concepts were ranked on a scale of 1 to 5, 5 being the best system, 1 the worst, for

Figure 4-5. Conceptual System Factors

Ship Motion Decoupling

- Motion Compensating Winch
- Cable Riding Instrument Platform
- Depressor Towed Instrument Platform

Instrument Body Control

- Active
- Passive

Depressor Control

- Active
- Passive

Table 4-6. Conceptual System Evaluation

SYSTEM			Existence of Previous Systems	Ship Motion Decoupling	Cable Vib. Decoupling	Simplicity	Handling Ease	Tension Var. (5 = least)	Vol.& Weight (5 = least)	Risk (5 = least)	Cost (5 = least)	Weighted Evaluation
Decoupling Technique	Instrument Platform Control	Depressor Control		10	8	2	2	1	2	5	3	
MCW	P	-	IOS	3	1	4	5	5	3	5	5	107
MCW	A	-		3	1	4	5	1	5	4	5	102
CRIP	A	P	SCRIPPS, APL	3	3	2	1	5	3	3	5	101
DTIP	A	P	WHOI	2	5	3	3	5	2	1	3	95
DTIP	A	A		3	5	2	3	1	3	1	3½	102.5
DTIP	P	A		2	5	3	3	1	2	1	3	91
DTIP	P	P		1	5	5	3	5	1	1	2½	85.5
MCW + CRIP	A	P		4	3	1	1	5	3	3	1	97
MCW + DTIP	A	A		5	5	3	3	5	3	1	1	121

each of the criteria listed along the top. Each of these criteria were then given a relative weight on a scale of 1 to 10, shown at the top of each column. Ship motion decoupling was considered to be most important and was given a 10 and similarly for the other criteria. The weighted rankings were then totaled and are given in the right hand column. While one can argue over the exact numbers chosen, the last concept, the depressor towed instrument platform with a motion compensating winch, rates far enough above the others to make it the obvious choice. This is in fact the concept which the IOS group was considering to improve the performance of their system. While considerable effort has been put into development of the CRIP type system, which has excellent potential for decoupling of vertical cable motions, it does not appear capable of decoupling horizontal cable motions in the ship motion frequency range, which is the reason it was rated with only a 3, by itself, and a 4 even in conjunction with an MCW. If, for example, one calculates the velocity gradient spectral level of Figure 2-2 associated with, say a 1 cm rms horizontal body displacement over the frequency range 0.2-1 Hz, at a tow-speed of 4 knots one finds a level of about 1×10^{-2} in the 0.1 to 0.5 cpm (2 to 10 m wavelength range). This represents a significant contamination of the fine structure velocity data. The rms acceleration corresponding to this level is about .015 g which is on the order of that measured during initial testing of the Scripps system in the San Diego Bay[18]. While it is not clear that contamination of horizontal components of fine structure velocity data can be adequately eliminated by any technique, the depressor towed instrument platform with motion compensating winch concept appears to have the greatest potential for minimizing it.

Electronic Approach Evaluation

Refering to Figure 2-2, if we desire body acceleration levels in the finescale range to be on the order of 10^{-5} $(m/s\text{-}m)^2$/cpm in order to

avoid contamination of the $\epsilon = 10^{-4}$ curve, then we require the rms acceleration level (over say .2-1 Hz at a speed of 2 m/s) to be less than

$$a_{rms} = \sqrt{\left(10^{-5} m/s^2\right)\left(2\ m/s\right)\left(1-.2\ Hz\right)}$$

$$= 4 \times 10^{-3}\ m/s^2$$

$$0.0004\ g$$

Although possible, it is not likely without considerable development effort that any physical approach will be able to reduce acceleration levels in the .2-1 Hz frequency range to such a low level. Consequently, electronic motion compensation techniques using simultaneous accelerometer measurements should be given due consideration to determine the exact degree to which velocity sensor motion effects can be rejected from the sensor output signal. Assuming that the velocity sensor and accelerometer motions are the same, or a least proportional, which will be true provided the sensor and accelerometer are in reasonable proximity to one another and the frequency range of interest is not too high (.2-1 Hz should be no problem), then the question becomes one of the stability of the velocity sensor and accelerometer outputs in order to maintain a reasonable common mode rejection ratio. Real time calibration techniques would probably have to be employed to ensure the continued validity of the compensated data. One such technique is to apply a mechanical shaker to the sensor/accelerometer package during periods of low velocity signal. Another is cross correlation to determine the exact magnitude of the common component.

Since seismic accelerometers are available with a noise floor on the order of 5×10^{-6} g rms over the frequency range 0.1-100 Hz, the real question is the stability of hot film velocity sensors which will determine the frequency of real time calibration required and whether or not a single frequency or a broadband calibration must be performed. While to our

knowledge, motion compensation has not as yet been attempted for towed velocity sensors, it should be relatively straightforward to test its effectiveness.

4.2.4 Conclusions and Recommendations

Based on existing data, the IOS system is, and the Scripps and APL systems appear to be, capable of meeting the requirements for fine and microscale measurements of temperature and conductivity. Although supportive data is lacking the IOS system appears, based on discussions with IOS personnel, by-and-large adequate for microscale velocity measurements but inadequate for fine scale measurements, except possibly under very low sea state conditions. The Scripps and APL systems, as they exist, are not satisfactory for either finescale or microscale velocity measurement because of the high vibration levels. The addition of a vibration isolation mount would probably allow satisfactory performance over the microscale range but not the finescale range.

Improvement of finescale velocity measurements for all systems requires one or both of two techniques. The first is by increased physical decoupling of ship motions of which the most promising approach appears to be the addition of a secondary body, towed behind and below the existing body. This approach is, however, only practical for the IOS system. The other technique is electronic motion compensation using simultaneous accelerometer data. Although the exact effectiveness of this technique is unknown, a rejection of at least 10 to 1 should be achievable.

Since electronic motion compensation is applicable to velocity measurements with all systems, since physical decoupling techniques will probably never totally achieve the body motion suppression required at fine scales, and since electronic compensation is the less expensive of the two techniques, it is recommended that this technique be investigated to determine its effectiveness before beginning additional towed body development

work. Based on the degree of motion compensation achievable, it will then be possible, from accelerometer data of existing towed body motions, to determine the additional motion suppression required by physical techniques. At that point, if warranted, model development and tow tank experiments of the decoupling afforded by a secondary towed body should be initiated.

A motion compensation investigation would be relatively simple and would employ a shaker table with a three dimensional motion capability. A velocity probe/three-axis accelerometer package would be mounted on the table in a flow tank and the probe response to motion in various directions over the corresponding finescale and microscale frequencies would be measured. Limitations due to drift, noise and other effects would then be determined to predict the degree of motion rejection feasible under realistic conditions.

Section 5

SUMMARY

A study was performed to determine if existing towed oceanographic measurement systems can meet, or can be modified to meet, the Navy's requirements for measurement of the finestructure and microstructure of temperature, salinity and velocity in the upper ocean. The results, in summary, are: (1) existing instrumentation is by-and-large adequate, the major areas of difficulty being the limited frequency response of temperature sensors and fouling and temperature contamination of heated film velocity sensors; (2) towed body requirements for temperature and salinity measurements can generally be met by one or more existing towed body systems, and (3) ship motion decoupling techniques employed by existing systems do not appear adequate to allow velocity measurements over the full amplitude and spatial frequency range of interest except in very calm seas. The overriding consideration in the suitability of the towed body system is the contamination of horizontal temperature and salinity fluctuation measurements due to vertical motion of the body in the presence of vertical structure and contamination of velocity data due to body sensor motion along the corresponding axis. A consequence of this is the need during towed measurements to monitor sensor motion over the entire measurement frequency range and the need to measure the local vertical temperature and salinity structure in order to place confidence limits on horizontal tow data and/or to employ motion compensation techniques.

Two types of techniques to improve velocity measurement performance were considered. The first, termed the physical technique, was based on physical system modifications to increase the ship motion decoupling at the towed body carrying the sensors. Based on three types of ship motion decoupling techniques and two other primary system characteristics, several conceptual systems employing existing technology were defined and rated using a number of performance criteria. The towed body system which rates

highest consists of a motion compensating winch for primary ship motion decoupling, an actively controlled depressor for primary depth control and an actively controlled secondary body containing a complete sensor package towed behind and below the main depressor. The secondary body provides primary tow cable vibration decoupling and secondary ship motion decoupling. Additional vibration decoupling can be employed via a soft attachment at the secondary body tow point and a sensor vibration isolation mount. An added advantage of the motion compensating winch is that temperature, conductivity and depth sensors can be employed on the main depressor and along the tow cable to collect additional information regarding vertical and horizontal structure and correlation properties.

The other technique, termed the electronic technique, employs electronic motion compensation using simultaneous accelerometer data. While this technique has apparently not yet been employed in practice, it should be relatively straightforward and inexpensive to investigate and determine its effectiveness.

Since existing fine and microscale towed measurement systems have been found to be inadequate if both finescale and microscale velocity measurements are to be included in addition to temperature and salinity measurement, and since velocity measurements are crucial to an understanding of the physics of ocean turbulence generation and dissipation, it is recommended that: (1) electronic motion compensation using simultaneous accelerometer data be investigated to determine the degree of compensation possible under realistic conditions and (2) model and tow tank experiments be performed to determine the additional ship motion decoupling afforded by a secondary towed body.

References

1. Monin, A.S., V.M. Kamenkovich and V.G. Kort, Variability of the Oceans, Wiley-Interscience, 1971, Chapter 3, "Small Scale Phenomena".

2. Gargett, A.E., "Microstructure and Fine Structure in an Upper Ocean Frontal Regime", J. Phys. Ocean. 83, 5123, 1978.

3. Gargett, A.E., "An Investigation of the Occurrence of Oceanic Turbulence with Respect to Finestructure", J. Phys. Ocean. 6, 139, 1976.

4. Garrett, C. and W. Munk, "Internal Wave Spectra in the Presence of Fine Structure", J. Phys. Ocean. 1, 196, 1971.

5. Joyce, T.M., and Y.J.F. Desaubies, "Discrimination Between Internal Waves and Temperature Finestructure", J. Phys. Ocean. 7, 22, 1977.

6. Gregg, M.C., C.S. Cox, and P. W. Hacker, "Vertical Microstructure Measurements in the Central North Pacific", J. Phys. Ocean. 3, 458, 1973.

7. Gregg, M.C., "Microstructure and Intrusions in the California Current", J. Phys. Ocean. 5, 253, 1975.

8. Osborn, T.R., "Vertical Profiling of Velocity Microstructure", J. Phys. Ocean. 4, 109, 1974.

9. Schedvin, J.C., C.H. Gibson, and T. K. Deaton, "Preliminary Results of a US - USSR Oceanic Microstructure Intercomparison Experiment", (to be published).

10. Cooper, J.W., and H. Stomell, "Regularly Spaced Steps in the Main Thermocline Near Bermuda", J. Geophys. Res., 73, 18, 1968.

11. Irish, J.D., and W.E. Nodland, "Evaluation of Metal-Film Temperature and Velocity Sensors and the Stability of a Self-Propelled Research Vehicle for Making Measurements of Ocean Turbulence", Oceans '78, IEEE, 1978.

12. Gibson, C.H., and R. B. Williams, "Development of an Acoustic Vorticity Meter", Triadic Research, Inc., Contract N00014-77-C-0287.

13. Gibson, C.H., and T.K. Deaton, "Hot/Cold Sensors for Velocity/ Temperature Ocean Microprocess Detection", in Instruments and Methods in Air-Sea Interaction, R. Davis, F. Dobson, and L. Hasse, eds., NATO Air-Sea Interaction Panel (to be published).

14. Nasmyth, P.W. "Techniques of Measurement from Towed Vehicles and Submersibles", in Instruments and Methods in Air-Sea Interaction, (see Reference 13).

15. J.G. Dessureault, "'Batfish', a Depth Controllable Towed Body for Collecting Oceanographic Data", Ocean Engin., 3, 99, 1976.

16. Morey, K.A., and E.L. Mollo-Christensen, "Design, Development, and Field Trials of a Towed Instrumented Glider", MIT Dept. of Meteorology, Report No. MITSG 76-20, 1976.

17. Katz, E.J., and W.E. Witzell, Jr., "A Depth Controlled Tow System for Hydrographic and Current Measurements with Applications", Deep Sea Res., 26, 579, 1979.

18. Gibson, C.H., "Development of a Towed Ocean Profiling System", Triadic Research, Inc., Final Report, APL/JHU Contract No. 600639.

19. Sumney, D.C., N.S. Smith, K.W. Watkinson, and D.E. Humpreys, "Hydrodynamic Stability and Control Analysis of GTOPS Vehicle", NCSC TR-323-78, Naval Coastal Systems Center.

20. Gibson, C.H., MILE Workshop Viewgraphs, unpublished, 1978.

21. Venezia, W.A., "Initial Report, Tip Profiling Response", DAEMON Prep, St. Croix, April 1979, APL/JHU.

22. Venezia, W.A., "Towed Ocean Profiling System (APLTOPS) Project Description", APL/JHU STT-79-026, 30 January 1979.

23. Brisbane, A., L. Custer, and D. Walters, "Approaches to Real-Time Measurement of the Motions of a Modified Mine-Sweeping Depressor", MAR Technical Report No. 221, April 1979.

24. Conti, U., P. Wilde, and T. L. Richards, "Towed Vehicle for Constant Depth and Bottom Contouring Operations", Offshore Technology Conference, Paper OTC 1456, 1971.

25. Widditsch, H.R., "SPURV - The First Decade", APL-UW 7215, October 1973.

26. "Summary Update and Recommendations for NAVOCEANO Environmental Support Program for SSBN Security," NAVOCEANO Letter Serial S973, 8 September 1978.

APPENDIX

Additional Towed Body System

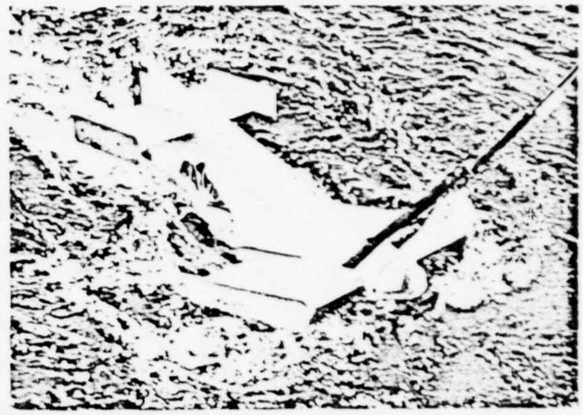
Information

Batfish

The following pages include a copy of a Batfish data sheet and an article from "Ocean Engineering" by its designer J. G. Dessureault. The pitch and roll motions mentioned in Section 3 are shown in Figure 6. In particular, pitch and roll motions during climbing and diving in Figures 6c and 6g are rather erratic and would most certainly contaminate finescale velocity data. The vibration levels mentioned in Section 3 are discussed on Page A-13. The 0.1 g rms acceleration over the frequency range 4 to 50 Hz mentioned, corresponds to a velocity gradient spectral level of about 5×10^{-3} in the spatial frequency range 1 to 12.5 cpm at a speed of 8 knots (14.8 km/hr). Referring to Figure 2-2, this represents a significant contamination level at the lower microscales, about an order of magnitude above that of the Scripps towed body.

'Batfish' Series 8800 Programmable Towed Body

Bulletin 7670



Batfish is a programmable towed body developed at the Bedford Institute of Oceanography at Dartmouth, Nova Scotia, Canada and manufactured under licence by Guildline Instruments. Batfish is a versatile platform for rapid gathering of oceanographic data. The electro-mechanical towing cable transmits sensor signals to the ship's data aquisition system and a command signal to the Batfish from an on-deck programmer. The Batfish may be commanded to 'fly' a predetermined profile or to maintain a constant depth. Power to actuate the Batfish control hydroplanes is provided by a hydraulic pump driven by an impellor. Batfish is light and compact – small enough to be deployed from a vessel only 15 metres in length. It is stable, durable and fast. Accelerometer studies confirm a three axis stability to ±5 degrees.

Construction is reinforced fibreglass, stainless steel and aluminum. An operating depth of 400 metres can be achieved with the standard Model 8801, towing speeds to 14 knots. Only 600 metres of faired cable is required.

A 'bottom avoidance' circuit coupled to the towing vessel's depth sounder is available to reduce the risk of accident in shallow waters. Available sensors are CTD (Conductivity, temperature and depth – Guildline Series 8700) and a fluorometer for dye studies, chlorophyll and turbidity measurement (Impulsphysik Variosens). An electronic copepod counter is under development.

Guildline offers complete 'turnkey' systems capability including all handling equipment, cable, winch, recorder and interface hardware to datalogger or on-line computer.

Batfish has undergone extensive trials and evaluation by the Bedford Institute, the Canada Centre for Inland Waters, the University of Washington and the Institute of Oceanographic Sciences, U.K.

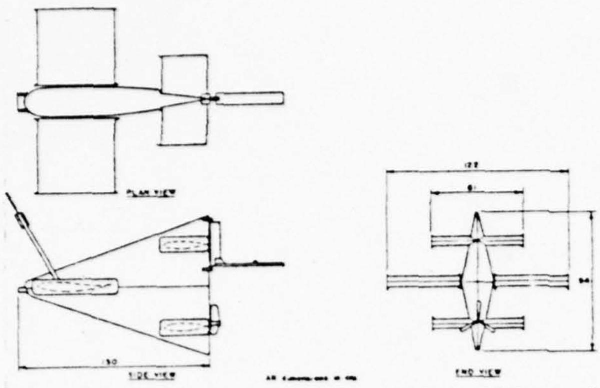
This brief bulletin comprises only a general description of the system in order to invite further discussions based on individual requirements. Requests for complete technical proposals are solicited.

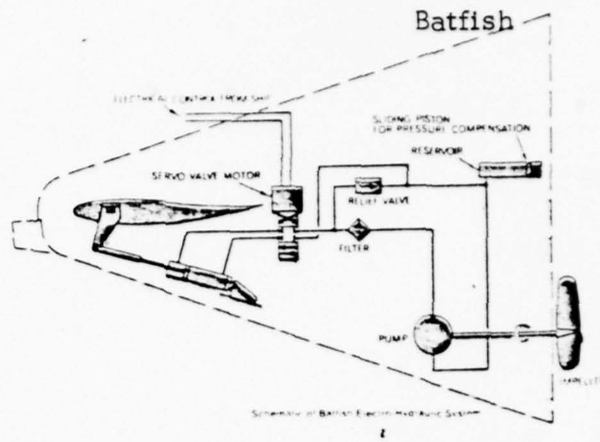
SYSTEM DESCRIPTION

The Guildline Batfish system may comprise one or more *of the following units:*

- Hydraulic System and Servo-Control
- Armored Towing Cable with seven conductors, terminated at each end. Operation below 100 meters *requires 'Flexnose' Fairing* by Fathom Oceanology Limited.
- *Winch and Sheave Block for faired or unfaired cable.* A more complex system is available for Flexnose Fairing.
- Slipring and terminated electromechanical cable from winch to depth control unit.
- Depth Control Unit provides facilities for manual and automatic sawtooth wave with adjustable up and down rate control. This includes a two channel display to monitor depth and command.
- Tension Monitor for towing cable.
- Instrumentation package to suit customer – Series 8700 Electronic Bathythermograph or Conductivity Temperature and Depth package by Guildline Instruments.
- Impulsphysik Variosens Fluorimeter.
- Copepod Counter under development.
- Special recording and display of data in analog or digital form as specified.
- Bottom Avoidance option coupled to ship's depth sounder for operation in shallow water.

Batfish





SPECIFICATIONS

Operating Depth

Speed	Cable	Depth
5 to 10 knots	300 metres unfaired	100 metres
5 to 10 knots	300 metres faired plus 200 metres unfaired	300 metres
5 to 10 knots	600 metres faired	400 metres

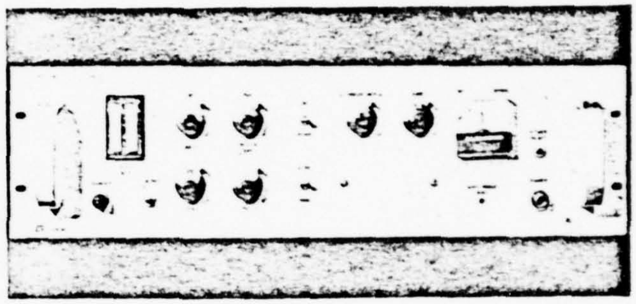
An additional unfaired cable length of 50 metres for winching turns and ship to surface is required.

Towing Cable (For use with Model 8703 CTD)

Length	330 metres
Diameter	0.81 cms
Breaking strength	4.3 metric tons
No. electrical conductors	7

Dimensions

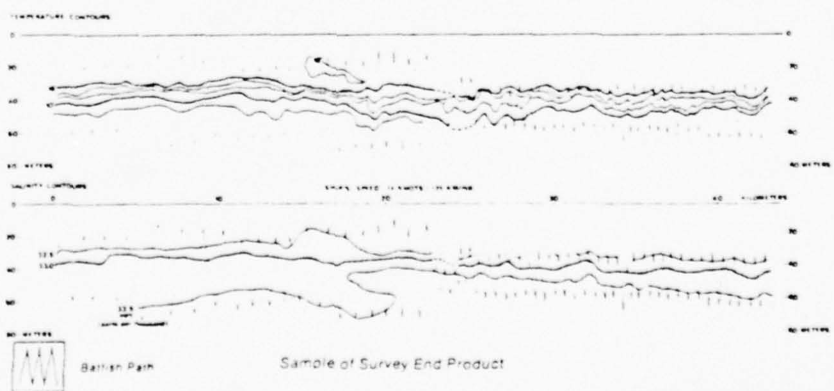
Length	1.3 metres
Height	0.9 metres
Wing Span	1.2 metres
Weight in air	70 k grams



DECK CONTROL UNIT

Model 88100 Batfish Control Unit provides manual and automatic depth control through a closed loop servo system. The manual command is in the form of a 10 turn potentiometer. In the automatic mode 10 turn potentiometers are used to set upper and lower depth limit, rate of ascent and descent, and bottom avoidance limit. Meter indications of command and actual depth, and servo control current.

Specifications subject to change without notice.



Batfish Path   Sample of Survey End Product

GUILDLINE INSTRUMENTS, INC.

1997 Palmer Avenue, Larchmont, New York 10538
Telephone (914) 834-8100

Represented by:

"BATFISH" A DEPTH CONTROLLABLE TOWED BODY FOR COLLECTING OCEANOGRAPHIC DATA*

J.-G. DESSUREAULT

Metrology Division, Atlantic Oceanographic Laboratory, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada

Abstract—"Batfish" is a streamlined vehicle developed to house fast-responding oceanographic sensors. It is towed behind a ship or small vessel and its depth is controlled from the vessel by a manually or automatically produced command signal. Variable-angle wings permit the vehicle to be lowered and a novel control surface, which eliminates the need for heavy ballast, assures lateral stability. There are two models: the standard and the wide-wing Batfish. The standard Batfish has collected temperature and conductivity data at depths of up to 200 m when towed at 10–25 km/hr, and the wide-wing Batfish at depths to 400 m when towed at 10–16km/hr.

1. INTRODUCTION

THE TOWED body described in this report was developed as a vehicle to carry fast-responding sensors at depths controllable from a vessel travelling at speeds of up to 25 km/hr. This system can produce quasi-continuous records, of the parameters sensed, in the horizontal and the vertical directions and can be worked from relatively small vessels such as those used for inland water surveys.

The design of a body to move through any fluid is a complex problem. Although the theory is well established for airplanes, only within the recent past have there been any publications related to the design of bodies towed through water (Strandhagen, 1963; Richardson, 1965; Patton, 1966; Laitinen, 1967; Eames, 1967; Jeffrey, 1968). While there are similarities between the hydrodynamic and aerodynamic cases, the high hydrodynamic-to-gravity force ratio and the use of a towing cable from a moving ship increase stability problems.

The ideal vehicle would be a self-propelled body (small remote-controlled submarine) independent of a surface vessel, but the cost of a small power plant and an underwater guidance system for such a body prompted us to consider towed systems only.

In towed systems, the hydrodynamic drag on the towline must be overcome in order to reach the operational depth. The most direct method of controlling the depth is to have a ballasted body and to vary the depth by varying the length of the towline; however, a major problem with this method is the need for a heavy-duty, high-power, and high-speed winch required to undulate the towed body within desired patterns. Since such equipment is not compatible with continuous operation from a small boat, this type of system was not pursued.

The concept chosen is a light towed body with varying-angle wings. A stabilizer maintains roll and yaw stability at all depths, and a close-loop servo-control system allows programming of any depth patterns within certain rates and limits of diving.

The two important objectives of maximum depth and speed are met by two models called the "standard" and the "wide-wing Batfish". The standard Batfish reaches the

*Bedford Institute of Oceanography Contribution.

allowable tension at high speed, while the wide-wing Batfish produces the same maximum tension at a lower speed and hence reaches greater depths.

Some time after this project was started, in 1966, the author learned about similar approaches, in Germany (Joseph, 1962), in the U.K. (Glover, 1967; Burr, 1968), in the U.S.S.R. (Zhuravle, 1969) and in Spain (Cruzado, 1970). Other studies have also been carried out by Dornier Systems GmbH in Germany. There are, however, some differences in the methods of operation and results obtained. Batfish has a fast-response depth control, a high depressing-force to weight-in-air ratio, lateral stability under most conditions, and a wide speed range.

2. DESCRIPTION AND DESIGN CONSIDERATIONS

2.1 *Dimensions and weights*

A standard Batfish is shown in Fig. 1. It is 1·3 m long, 0·9 m high and 0·75 m wide. It weighs 70 kg in air and approximately 20 kg in water. The wide-wing Batfish differs only by the size of its wings, the length of the towing bar, and the stabilizer's weight. Its overall width is 1·25 m and it weighs 85 kg in air and approximately 25 kg in water.

2.2 *The body*

The body has a low-drag streamline contour. Its deep vertical profile was initially intended to increase the vertical distance between the centre of buoyancy and the centre of gravity in order to obtain maximum static righting moment. It proved to be insufficient at high speeds and a dynamic stabilizer had to be added. The static righting moment produced by the buoyancy at the top is still necessary for very low speeds and during the launching operation. The high vertical profile gives good roll and yaw damping, and also, provides a convenient structure on which to mount the horizontal tails clear of the wing's wake. This body shape is easily formed by running straight lines from the middle section contour to the top and bottom points of the tail.

The lower part contains the wing actuator system and the instrument tunnel. The upper part contains the electronics for the sensors. The tunnel which lets water flow through the body is intended to house a copepod counter. This tunnel forms a convenient base to mount the conductivity and temperature sensors and their electronics.

2.3 *The wings and the horizontal tails*

The depressing wings have a cambered airfoil section (NACA 6412) to get a maximum depression at the lower speeds. The standard wings are 25 cm wide and the wide wings are 50 cm wide; both have a chord of 50 cm. The sizes are designed to produce a maximum lift of 1100 kg at 25 km/hr for the standard wings and the same lift at 18 km/hr for the wide wings.

End-plates are used to increase the effective aspect ratio and keep the span to a minimum, which facilitates the handling and reduced the rolling moment of any asymmetry.

The wings are rigidly mounted on a shaft pivoted through the body and the internal mechanism turns this shaft to control their angle of incidence.

The dihedral angle of the wings is zero for two reasons: first, a fixed dihedral angle would have opposite effects at depth during diving and near the surface when Batfish is lifting the cable; second, the construction of a changing or fixed dihedral angle would have been more difficult.

The horizontal tails are symmetrical NACA 0015 airfoil profiles. Their lift resists the

gravity forces on the body and the pitching moment of the forewings. The chord of these foils is 30 cm and the span is 75cm. The foils are mounted at the top and bottom of the tail in order to keep them out of the upwash. This orientation, then, insures that the body always points in the travel direction. The lower tails are specifically designed to hold up the back of the body when towing at the surface. Without them, the back sinks in water and the forewings stay in a surface planing mode.

2.4 The stabilizer

The roll and yaw stabilizer consists of a vertical trim tab free-pivoted along the tail edge of the upper half of the body The trim tab is actuated by its own weight and the weight of the tail attached to it. When the body is tilted from the vertical plane, the force of gravity turns the trim tab, which produces a hydrodynamic force in the direction opposite to the tilt. This force has two distinct effects: (1) When the towing bar angle is near zero (Batfish near the surface) the trim tab produces a righting moment on the body to keep it vertical. (2) When the towing bar angle is near 90° (Batfish diving deep) the trim tab produces a steering force on the body towards the vertical plane of the towing vessel. This gravity controlled stabilizer (Canadian Patent Number 892,351) can stabilize a body with a high hydrodynamic-to-gravity force ratio and eliminate the need for heavy ballast to keep Batfish stable.

The trim tab is 30 × 7·5 × 3cm and the tail is 45 × 5 × 0·6 cm thick for the standard fish and 1·2 cm thick for the wide-wing fish. The total weight is 1·8 kg and the centre of gravity is 16 cm from the pivot line of the trim tab. The size of the stabilizer was decided by taking into consideration that the disturbing forces are small and the natural frequency of the stabilizer should be much higher than the natural frequency of roll or yaw of the towed body.

2.5 The wing actuator system and depth servo-control

The wings of Batfish are continuously adjusted by the electro-hydraulic actuator shown in schematic form in Fig. 2. The main components of the system are a hydraulic pump driven by an impeller in the slip stream, an electro-hydraulic servovalve, and a double-acting hydraulic cylinder. A relief valve set at 70 bars bypasses the excess fluid when the servovalve is only partly open. The total system is pressure compensated by a variable volume reservoir connected to the intake port of the pump. The first system was built from discrete compo-

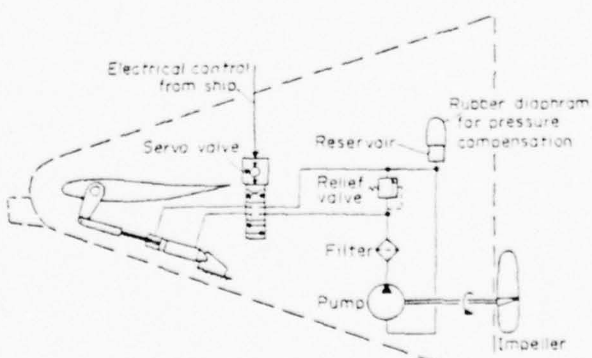


FIG. 2. Schematic diagram of the electro-hydraulic actuator.

nents inter-connected with copper tubes. It often developed leaks and salt water contaminated the expensive and sensitive servovalve. The present system consists of a solid aluminium block containing all the hydraulic elements. This electro-hydraulic system has the advantages of being small; it requires very little power (0–10 mA) to be transmitted through the towing cable, and can operate at any depth.

The depth servo-control system is illustrated in Fig. 3. The depth signal from the pressure transducer mounted in the Batfish is compared to a command signal generated on board the vessel and the difference between these two signals is converted into an electric current which is proportional to the error. This current is fed down to the servovalve, which in turn allows a flow of hydraulic fluid proportional to that current to move the piston of the hydraulic cylinder. After a few trials, a phase-lead compensation network was added to the servo-controller to improve the depth response to the command signal.

The controller panel, shown in Fig. 4, allows one to command the depth manually or to generate a triangular command signal with adjustable slopes and limits. A spring-centred toggle switch allows the operator to override the limit settings at any time. The gain of the servo-control can also be adjusted to get the best response.

A "bottom avoidance" system (Herman, 1975) was also developed to reduce the risk of accident in shallow waters. The circuit is coupled to the towing vessel's depth finder and it prevents the Batfish from getting below a preset depth above the bottom. When tripped, the circuit makes Batfish rise at a rate of 1 m/sec and starts an audible alarm.

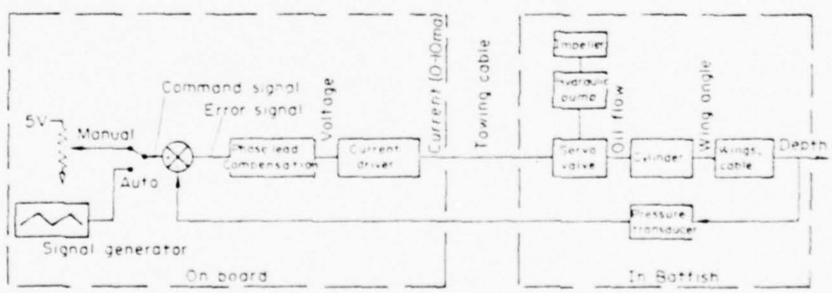


FIG. 3. Block diagram of the depth servo-control system.

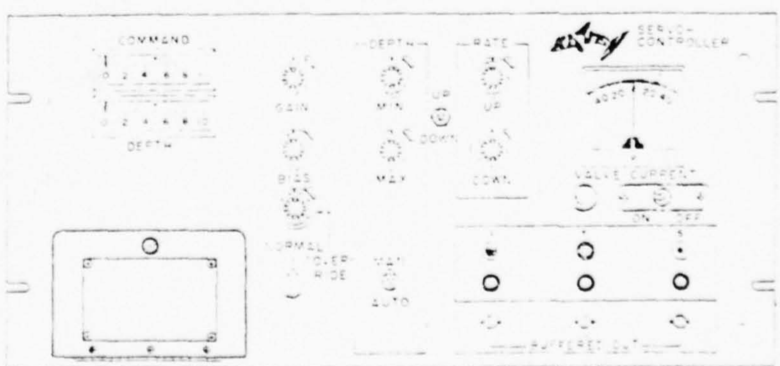


FIG. 4. Batfish controller panel.

2.6 The towing bar and the towline

The towing bar is pivoted on the wing shaft to transmit the hydrodynamic forces directly to the towline. Its angle is limited between 0 and 100°. The zero degree stop on the nose is needed to keep the fish stable since, if the towing point passes below the centre line of the body, the steering effect of the stabilizer sends the fish away from the towline and the resulting side pull makes the Batfish roll continuously. The nose stop does, however, cause high bending strains in the towing bar when towing through surface waves with a long towline sagging between the Batfish and the ship.

The towline is a seven-conductor electro-mechanical cable with a breaking strength of 4,000 kg. The first tows were done with bare cable, but later Flexnose fairing* was added to reduce the drag and vibrations. The fairing is 1·25 cm thick and is made up of 10 cm long pieces linked into 2 m sections which are free to rotate around the cable. The sections are separated by stopper sleaves crimped on the armoured cable. It is necessary for the fairing to be in individual sections and able to turn around and align itself with the flow direction when the Batfish is approaching the surface and the cable is sagging between the fish and the towing vessel.

3. PERFORMANCE EVALUATION

3.1 Test procedures

Batfish was tested from various ships ranging from a 10 m long boat for work in the Bedford Basin, Nova Scotia, to the 90-m long C.S.S. *Hudson* for work on the open sea. Most of the towing was done at speeds from 10 to 25 km/hr, but some was done at 6 km/hr. Towing was always done from the stern of the ship, through an A-frame, or a davit when unfaired cable was used. For towing with faired cable, the launching rig shown in Fig. 5 was used to avoid damaging the fairing during both launching and recovery of the Batfish in rough weather.

The primary goal of the experimental program was to develop a working system to carry scientific instrumentation, rather than study the dynamics of towed systems. Tests were run to determine the maximum depths and the depth responses to step and ramp commands at various speeds with both faired and unfaired cables of different lengths.

The experimental tests were done with full scale prototypes towed at sea. Work with a scale model was not practical because of the length of the towing cable (on which the behaviour of the system depends heavily), the high speeds involved, and the difficulty of remotely actuating the wings on a small model.

3.2 Instrumentation

The depth of Batfish, the most important parameter, is measured by a pressure transducer mounted inside the body where the pressure is equal to the static pressure, which is directly proportional to the column of water above.

The towing tension is measured with an electronic load-cell at the ship end of the towline only.

The pitch, roll, and towing bar angle were all measured with potentiometric pendulums. This type of instrument is sensitive to horizontal acceleration, but under stable conditions the acceleration is nil and it indicates the attitude accurately. The wing angle was measured with a one-turn potentiometer geared to the wings shaft inside the Batfish.

A three-axis accelerometer package was also used to monitor the towed body. The package was rigidly mounted and it measured the vibrations well; however, a gyro-stabilized

*Available from Fathom Oceanology Ltd., Port Credit, Ontario, Canada.

platform would be necessary to measure the true accelerations without the gravity components.

All the signals were transmitted through the seven-conductor towline and recorded on a six-channel analog recorder on board the vessel.

3.3 *Results*

The results of the trials are summarized in the following paragraphs where the maximum depths, depth response, pitch, roll, towing bar angle, accelerations, wing angle, and towing tension are discussed.

The maximum depth obtainable with a standard Batfish is approximately 200 m when it is towed with 330 m of faired cable at speeds of up to 25 km/hr. A wide-wing Batfish can reach 400 m when towed with 500 m of faired cable at speeds of up to 16 km/hr. With 300m of unfaired cable, the respective depths are 60 and 100 m.

The response of the system to various commands depends slightly on the towing speed and the length of the towing cable, and the following values are typical: at 16 km/hr with 300 m of faired cable, the response to a climbing or diving command of 1·5 m/sec has an error of 12 m from the command depth, or, in other words, 8 sec lag between actual depth and command depth, and at 25 km/hr with the same cable and a command of 1 m/sec the error is 8 m or 8 sec. Constant depth command is maintained within 1 m in most cases.

Samples of recording are shown in Figs. 6–10 to illustrate the tests results. Fig. 6 shows responses to step, ramp, and sinusoidal commands of a standard Batfish towed at speeds from 15 to 26 km/hr with 300 m of faired cable. One can see that a change in depth of 20 m takes less than 20 sec (Fig. 6a and 6f) and undulations of 15 m at a rate of more than 4 cpm (Fig. 6e) are possible. Figure 6(b) shows the response to a ramp command of 1·5 m/sec; the tracking began to fail below 150 m because part of the fairing was not in good condition.

The pitch and roll are also shown in Fig. (6a–g). The pitch is the angle of the body to the horizontal direction of travel through the water and is caused by the horizontal tails. At

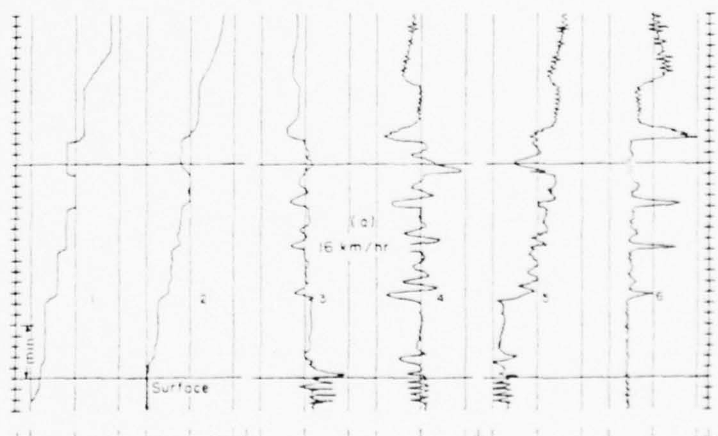


FIG. 6(a)

"Batfish"

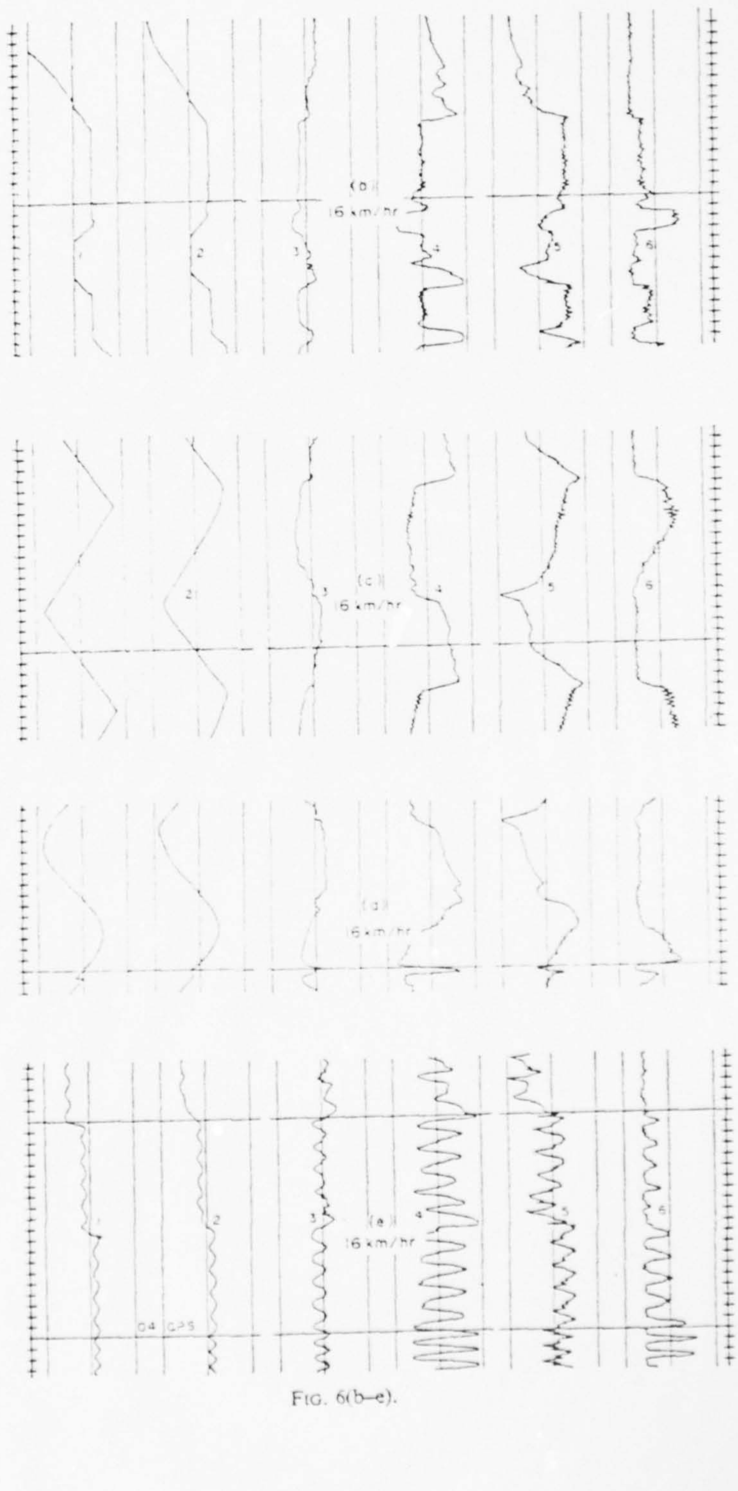


FIG. 6(b–e).

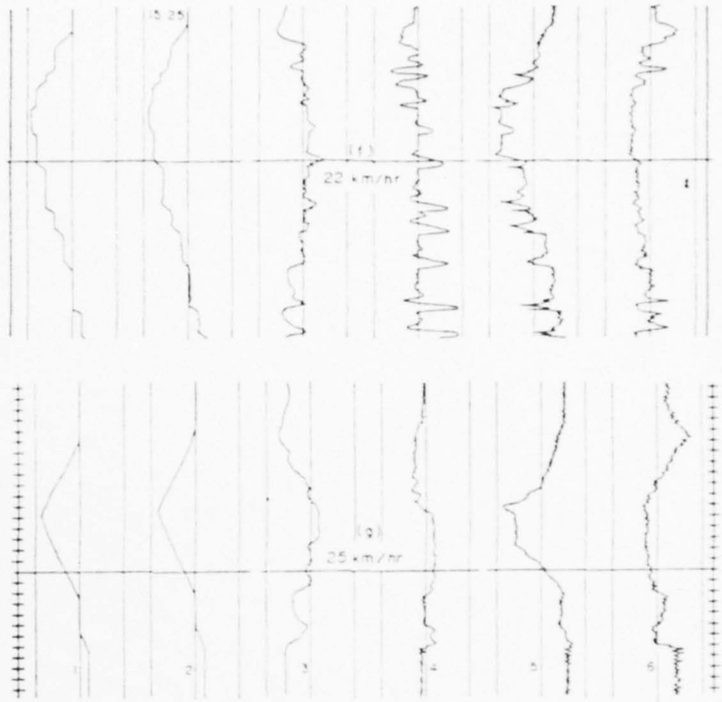


FIG. 6.(a–g) Samples of chart recording of command signal, depth, pitch, roll, towing bar angle, and *towing tension for a standard Batfish with 300 m of faired cable.*

constant depth, the pitch is zero and it varies to both + and −45° during manoeuvres. The fast motion (≃0·2 Hz) recorded is the response of the pendulum to the fore and aft acceleration caused by the ship motion through the seaway.

The roll is a measure of the vertical attitude of the Batfish. Ideally, it should be zero all the time; however, any asymmetry or disturbance tends to make the body go sideways, and is then resisted by the stabilizer. The roll recorded in Figs. 6(a–g) is not always zero because the Batfish used for these tests had its wings misaligned by almost 1°. One can see that the Batfish pulls to the side as the towing tension increases. At the beginning of record (a), the Batfish is at the surface and lies to one side because the top comes out of the water and there is nothing to keep it upright. As soon as it starts diving, the stabilizer begins to be effective and at 20 m the roll is steady at approximately + 8°. When the Batfish dives the tension increases and the roll goes negative but it does not overshoot, which is an indication of the good performance of the stabilizer. With a well-built Batfish, the roll can be less than 10° at all times.

Some tests were done without a stabilizer and the Batfish experienced a "cork-screw" motion when the depth command was changed swiftly.

The towing bar angle is the angle the cable makes with the horizontal at the Batfish. It is a direct measurement of the lift-to-drag ratio of Batfish, which varies with the wing angle. At shallow depths, i.e. 0–30 m, the fish is lifting the end of the cable and the towing bar is stopped on the nose and the angle is the same as the pitch angle. The recordings show a

difference of 10° *due to an offset of the potentiometer pendulum mounted on the towing bar.* Again, the 0·2 Hz "noise" on the trace is the pendulum response to the fore and aft acceleration caused by the ship's motion. The maximum angle measured was between 70 and 75°, which corresponds to a lift to drag ratio of around 3. Too high a ratio can result in instability in the longitudinal mode; so, it would not be advantageous to reduce the drag of the body.

The towing tension, which is measured on deck, is shown on channel number six of the recordings. At shallow depths the tension is mainly the force required to pull the faired cable longitudinally through the water. When the command is changed, for example, from 30 to 60 m in less than 10 sec, the tension builds up sharply from 200 to 500 kg and then drops back to about 250 kg. We know from other recordings, as that in Fig. 7, that the high tension corresponds to a large wing angle and higher body speed. As the Batfish speeds downward, the phase-lead compensation reverses the wing angle and, after a couple of over-shoots, the depth follows the command.

The wing angle was measured to better understand the depth response to the command signal. Figure 7 shows two interesting facts: (1) The wings move immediately with the depth command but it takes a few seconds (1–3 sec) before the depth starts to change. (2) The steady state difference in wing angle for a difference in depth of 20 m is very small, i.e., approximately 2°.

The standard Batfish also performs very well with unfaired cable for shallow surveys. Figure 8 shows depth and command signal for a standard Batfish with 65 m of unfaired cable towed at 13 km/hr.

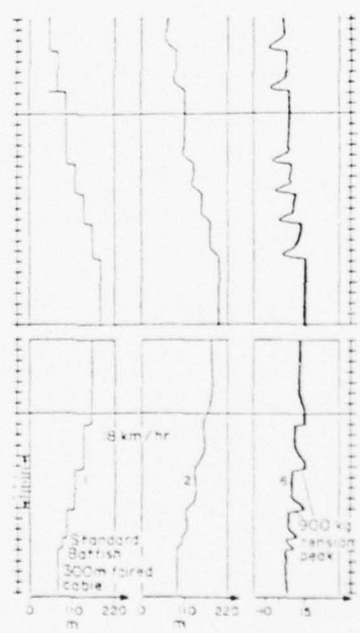


FIG. 7. Chart recording of wing angle, command signal, and depth for a standard Batfish with 300 m of faired cable.

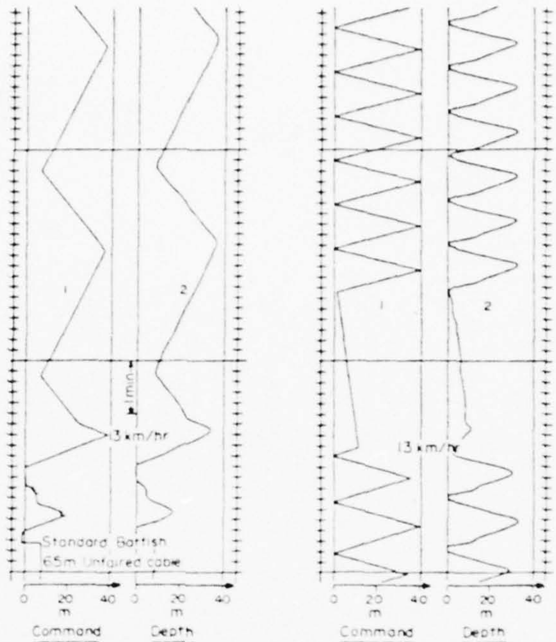


FIG. 8. Chart recording of command signal and depth for a standard Batfish with 65 m of unfaired cable.

The wide-wing Batfish was built for deep surveys, i.e., up to 400 m. Figure 9 shows a sample recording of command signal, depth, and towing tension of a wide-wing Batfish towed at 15 km/hr with 600 m of faired cable. Figure 10 shows a recording with a wide-wing Batfish towed at 18 km/hr with 100 m of faired cable over a shallow spot in the middle of the St. Lawrence River. The depth channel of the recording is marked with the actual soundings of the depth of water under the ship.

Some acceleration measurements were taken using a standard Batfish at velocities of 10 and 16 km/hr and a power spectrum showed that the vibrations in any of the three modes were less than 0·1 g rms for any frequencies from 4 to 50 Hz. At 20 km/hr the peak-to-peak amplitude was about 0·7 g at 40 Hz. It is believed that most of the vibration is produced by the hydrodynamic flow around the wings because the vibration increases with the towing tension. Since the towing cable used was faired only a small amount of vibration should have been produced by it.

4. SCIENTIFIC APPLICATIONS

Batfish was first used to measure temperature vs depth in the Great Lakes, then to measure temperature and conductivity versus depth in the Atlantic Ocean (Bennett, 1972) and the St. Lawrence Estuary. It has also been used to do a dye tracing experiment and to measure chlorophyll *a* off the coast of Nova Scotia (Herman, 1975). The instruments used were Guildline TD and CTD, and the Impulsphysik Variosens Fluorometer.

Other instruments will soon be operational. A pumping system to collect water at various depths from a moving ship is being built at the University of Washington in Seattle, Washington, and at the Canada Centre for Inland Waters in Burlington, Ontario. An

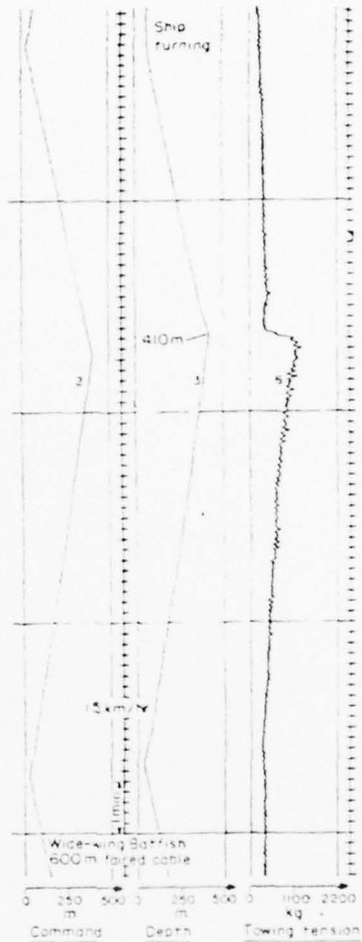


FIG. 9. Chart recording of command signal, depth, and towing tension for a wide-wing Batfish with 600 m of faired cable.

electronic copepod counter is also being developed for the Bedford Institute of Oceanography.

5. SUMMARY

Batfish is a new towed vehicle for oceanographic sensors.* Its depth is continuously controlled from the towing vessel by either a manually or automatically produced command signal. It can maintain constant depth or move up and down at rates greater than 1 m/sec. A simple stabilizer makes possible large depressing forces with a light body. Batfish is small enough to be used from a 10 m long vessel for inland water surveys. In addition, the Batfish is capable of reaching depths of 200 or 400 m with wide wings which makes it useful in the ocean.

*Marketed under license by Guildline Instruments Ltd., Smith Falls, Ontario, Canada.

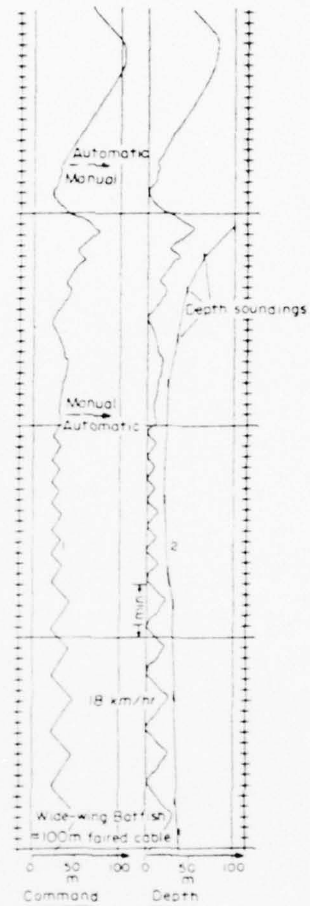


FIG. 10 Chart recording of command signal and depth for a wide-wing Batfish with 100 m of faired cable.

Acknowledgements—I wish to thank everyone who has contributed to the development of the Batfish system including Dr. R. L. G. Gilbert for his direction at the beginning of the project, Dr. A. S. Bennett for his advice and for his assistance in the instrumentation of the body, and Mr. J. Brooke for his guidance and his assistance in writing this paper. Special thanks are extended to Mr. S. W. Young for his technical help and to the officers and crew members on the ships C.S.S. *Hudson* and C.S.S. *Dawson* for their cooperation during the testing of the Batfish at sea.

REFERENCES

BENNETT, A. S. 1972. Some observations of salinity and temperature structure with a variable depth towed body. *Oceanology Int.* 72, 353–356.

BURR, P. 1968. An oceanographic data acquisition system. *A Critical Look at Marine Technology*, Marine Technology Society.

CRUZADO, A., JULIA, A. and BALLESTER, A. 1970. A remotely commanded depressor for continuous physical and chemical analysis. NATO Subcommittee on Oceanographic Research Technical Report No. 52. Brussels.

EAMES, M. C. 1967. Experimental bodies for high-speed underwater towing research. *Canad. Aeronaut. Space J.* 13, 208–208.

GLOVER, R. S. 1967. The continuous plankton recorder survey of the North Atlantic. *Symp. Zool. Soc., Lond.* 19, 189–210.

HERMAN, A. W., JOLLYMORE, P. and PHILLIPS, E. F. 1975. Bottom avoidance systems for batfish. Bedford Inst. of Oceanog., Report Series BI-R-75-3.

HERMAN, A. W. 1975. Chlorophyll and dye detection with the variosens fluorometer. Bedford Inst. of Oceanog., Report Series BI-R-75-2.

JEFFREY, N. E. 1968. Influence of design features on underwater towed systems stability. *J. Hydronaut.* 2, 205–213.

JOSEPH, J. 1962. Der Dolphin, Ein Messgeraet zur Untersuchung von oberflaechennahen. Temperatur. Schichtungen im Meere. *Deutsche Hydr. Zt.* 15, 16–23.

LAITINEN, P. O. 1967. Cable-towed underwater body design. rept 1452, U.S. Naval Electronics Lab., San Diego, Calif.

PATTON, K. J. and J. W. SCHRAM 1966. Equations of motion for a towed body moving in a vertical plane. Rept. 736, U.S. Navy Underwater Sound Lab., New London, Conn.

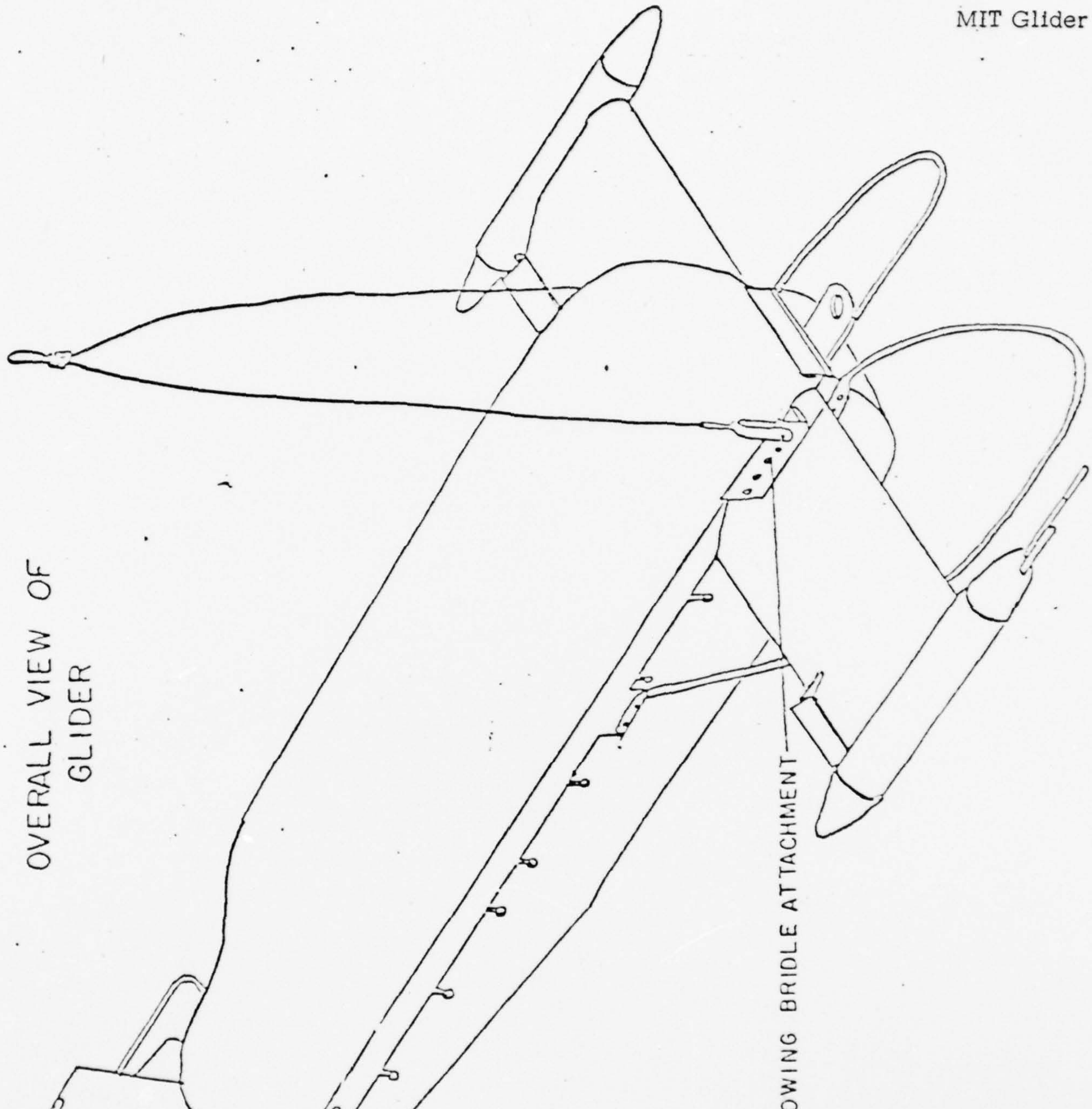
RICHARDSON, J. R. 1965. The dynamics of towed underwater systems. Rept. 56, Engineering Research Associates, Toronto, Canada.

STRANDHAGEN, A. G. and THOMAS C. F. 1963. Dynamics of towed underwater vehicles. Research Rept., U.S. Navy Mine Defence Lab., Panama City, Fla.

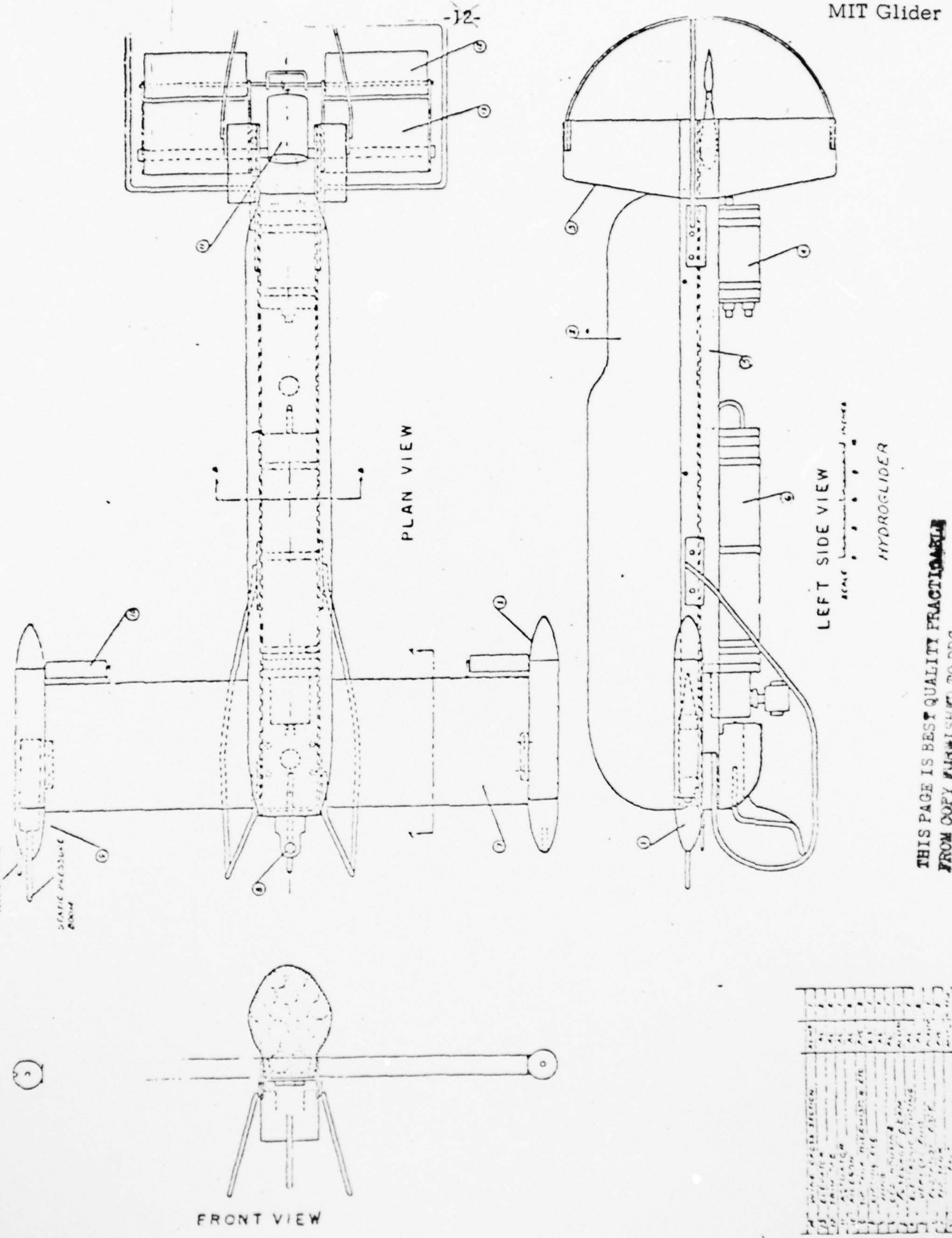
ZHURAVLE, V. F. 1969. A depressor for towed oceanographic instruments. *Oceanology, U.S.S.R.* 9, 138.

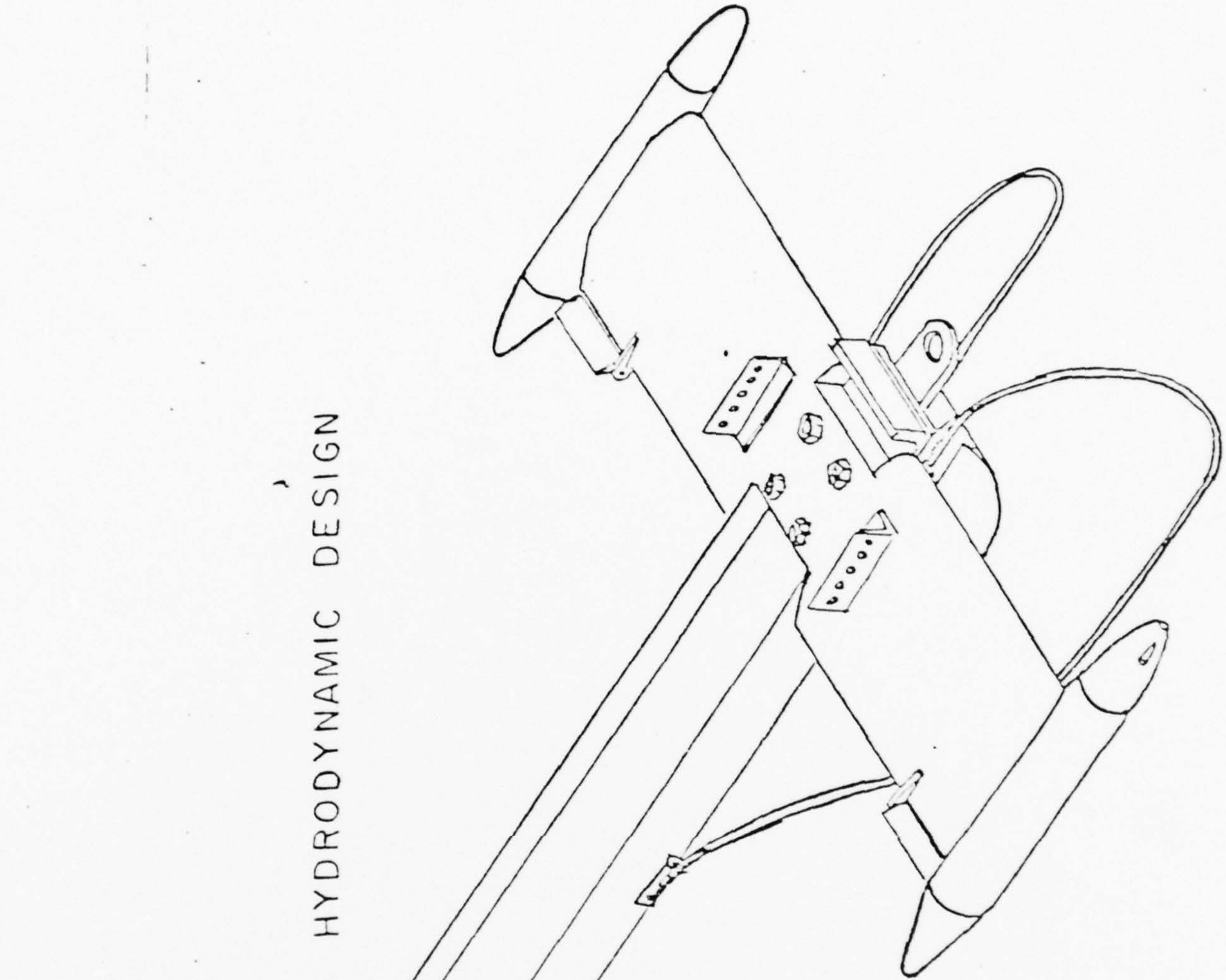
MIT Glider

The following pages contain additional information on the physical properties of the MIT Glider obtained from Reference 16. Other physical and electrical characteristics, as well as the performance of the depth control system, are discussed in that report.



OVERALL VIEW OF GLIDER


PLAN VIEW
LEFT SIDE VIEW
HYDROGLIDER
FRONT VIEW



HYDRODYNAMIC DESIGN

Wing area	4.5 ft^2	=	0.414 m^2
Wing span	4 ft	=	1.20 m
Wing chord	13.5 in	=	0.338 m
Aspect ratio	3.55		
Ailerons:			
Span	6 in	=	15.24 cm
Chord	1.25 in	=	3.17 cm
Fraction of semispan	1/8		
Area	7.5 in^2	=	48.4 cm^2
Vertical stabilizer:			
Area	1.36 ft^2	=	0.125 m^2
Height	28 in	=	0.71 m
Average chord	7 in	=	17.8 cm
Distance from wing 1/4 chord to vertical fin hydrodynamic center approximately:	69.4 in	=	1.763 m
Rudder	none		
Horizontal tail:			
Total area	1.103 ft^2	=	0.101 m^2
Distance from wing 1/4 chord to horizontal stabilizer 1/4 chord:	70 in	=	1.78 m
Elevator (servo elevator) area:	0.325 ft^2	=	0.029 m^2
Weight in air	175 lbs	=	79.5 kg
Buoyancy	200 lbs	=	90.8 kg
Excess buoyancy	25 lbs	=	11.4 kg

WHOI System

Depth control body

Length: 2.3 m

Wing Span: 1.5 m

Weight in Air: 160 kg

Weight in Water: 50 kg

Ship to control body cable

0.75 cm, single conductor armored, unfaired

Length: Approximately 7 x depth plus 500 m at 3 m/s

Control body to sensor fish cable

0.8 cm, multiconductor, flexible rubber helicopter fairings

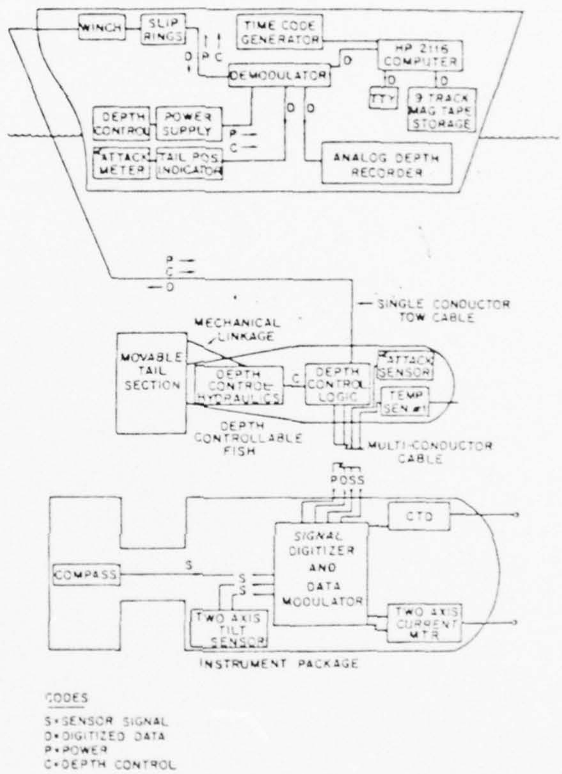
Length: As long as 75 m has beenused

Telemetry

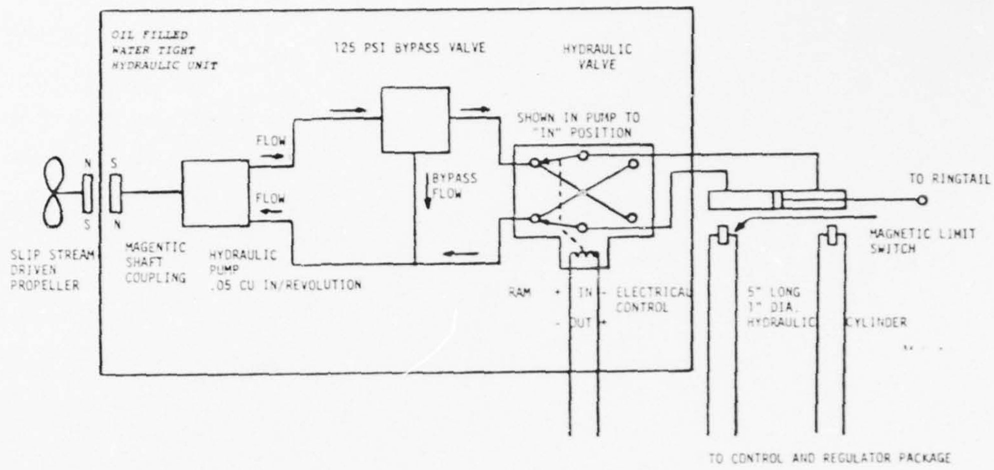
Teletype formatted FSK taken from NBIS CTD system

Depth control

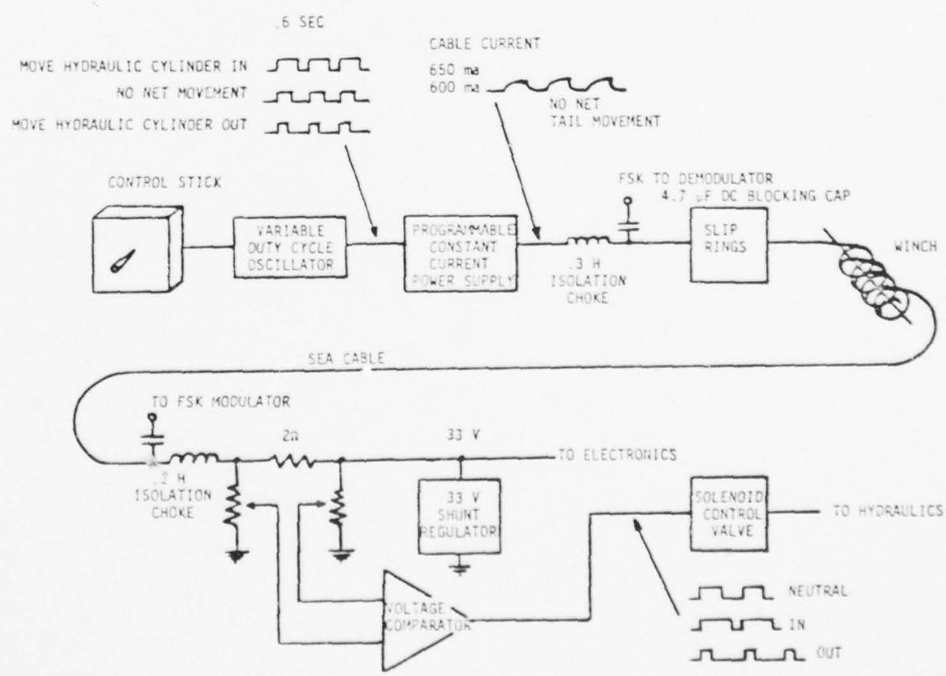
Manually operated control stick



Communication chain. The power and data links are through the data modulator in the sensor fish and the demodulator aboard ship. The depth control hydraulics and the depth control link are detailed in the next two figures.



Depth Control Hydraulics System

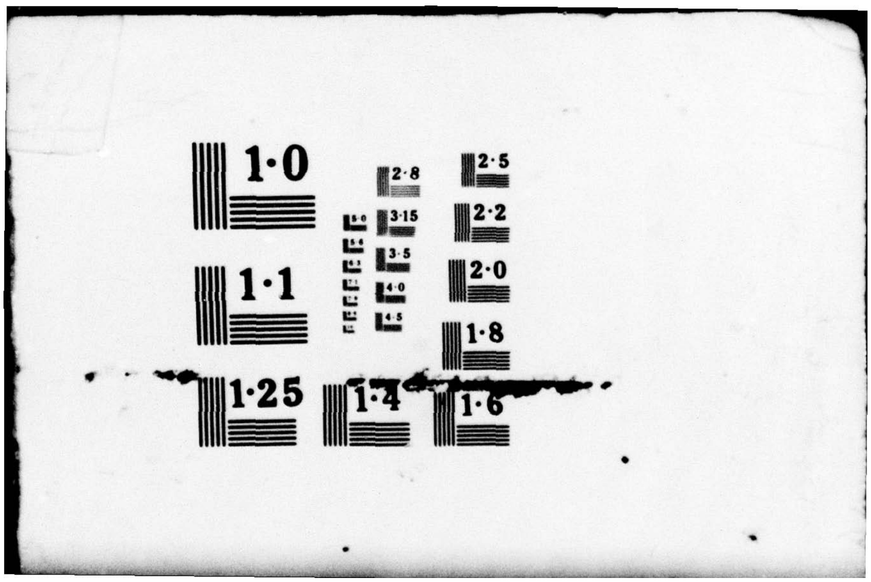


Depth Control Circuit

AD-A072 399 MAR INC ROCKVILLE MD F/G 8/10
A STUDY OF THE USE OF A TOWED BODY FOR OCEAN FINE AND MICROSTRU--ETC(U)
JUL 79 S H KOEPPEN N00014-79-C-0142
UNCLASSIFIED MAR-TR-226 NL

2 OF 2
AD
A072399

END
DATE
FILMED
9 - 79
DDC


1·0
2·8
2·5
3·15
2·2
3·5
2·0
1·1
4·0
4·5
1·8
1·25
1·4
1·6

IOS SYSTEM

Cable

Double armoured, approximately 2.85 cm diameter multiconductor core. Lower 100 meters faired with continuous rubber type fairing.

Vibration Isolation Mount

Water damped, spring mount with natural frequency of about 1 Hz. Peak-to-peak free travel approximately 10 cm on all three axes. In calm water, body structural vibrations and cable vibrations are barely discernable above noise from other sources. In higher sea states, mount hits stops with increasing frequency limiting usefulness of velocity data.

Motion Sensors

Rotor current meter for mean speed; depth gauge; two accelerometers to measure body attitude and vibration.

Motion Levels

Little data on depth keeping capability and none on vibration levels has been published by IOS, although a considerable amount of such data has been collected by the motion sensors mentioned above. The following on vibration levels was obtained via personal communication with Dr. Nasmyth of IOS.

Frequency Range	Major Source
0.2 - 1 Hz	Ship motions
1 - 2 Hz	Vibrating string modes of tow cable
2 - 5 Hz	Body structural vibrations
5 - 24 Hz	Cable Eddy-shedding
24 - 200 Hz	None (quite clean)

SCRIPPS SYSTEM

Body Physical Dimensions

(See APL System)

Support Cable

Stainless steel; 1/8 and 1/4 inch diameter and 5 m and 10 m lengths have been tested; presently unfaired.

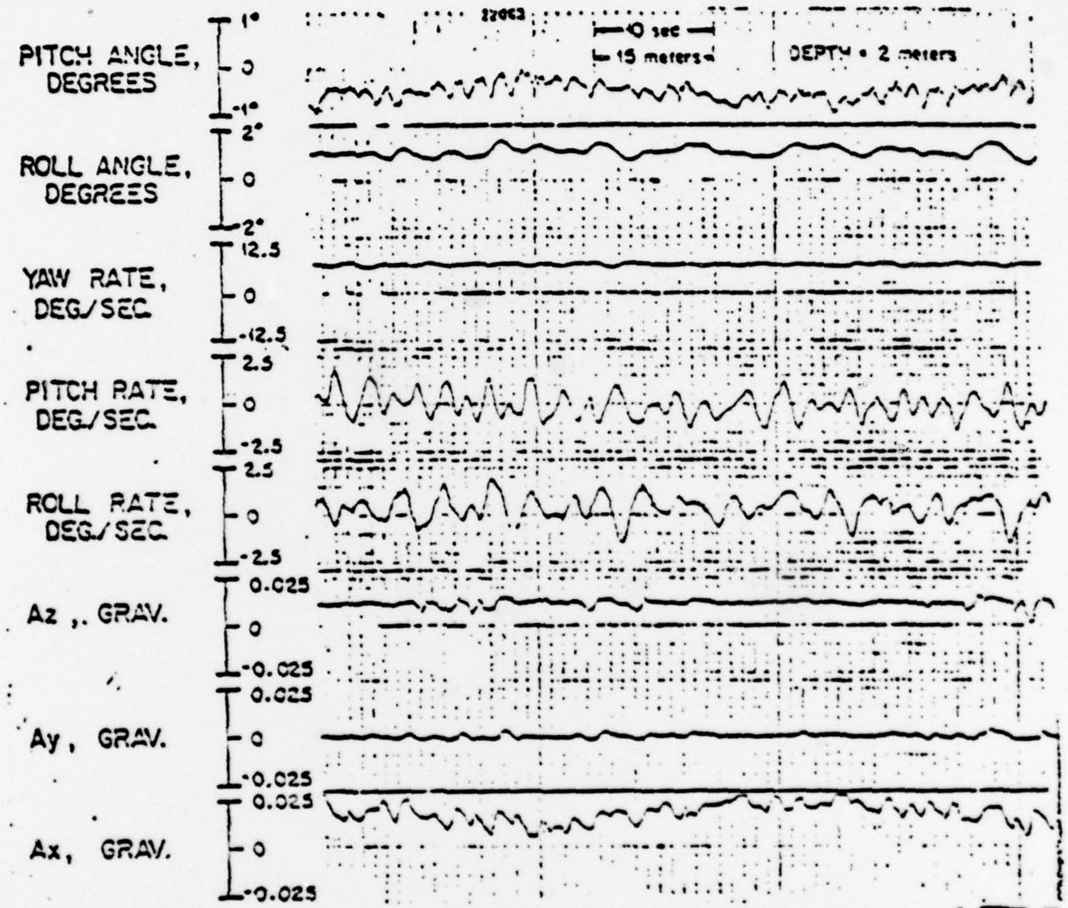
Tethers

0.3 inch diameter Sampson chord with 0.3 inch diameter Kevlar multiconductor data cable attached to upper tether; both are faired by a nylon velcro material; tether length is 3/4 that of support cable.

Tow Cable

Kevlar and steel multiconductor cables have been used; nylon-velcro fairing.

The following three figures show data obtained from References 18 and 20. The first figure is data from APL's motion monitoring package during initial testing of the Scripps system off the San Diego coast. Wind waves were 2-3 feet with little swell. The second figure is data from the MILE experiement. The pressure transducer data indicates an rms depth variation of about 25 cm with a period of approximately 6 seconds. The last figure is accelerometer spectra along the tow direction from MILE. The curve of Figure 2-2 is the same spectrum. The rms acceleration over the entire measurement frequency range is .029 g which is about twice that of the San Diego data, which is not surprising since the sea state, although unspecified, was undoubtedly higher. The peak in the spectrum at roughly 0.2 Hz corresponds closely to the frequency of depth oscillation of the preceeding figure.

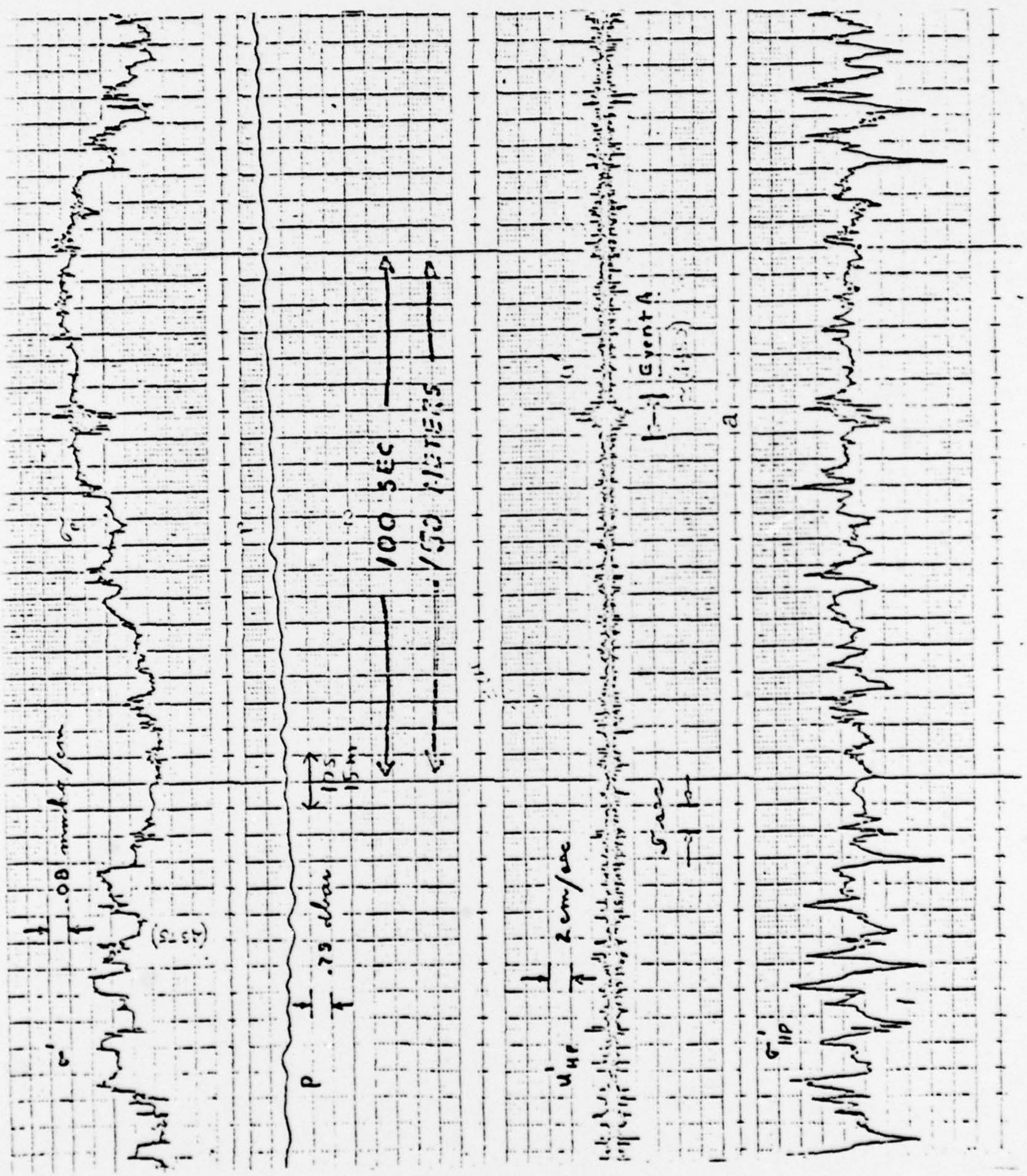


Motion Monitoring of Towed Ocean Profiling System (OTOPS)

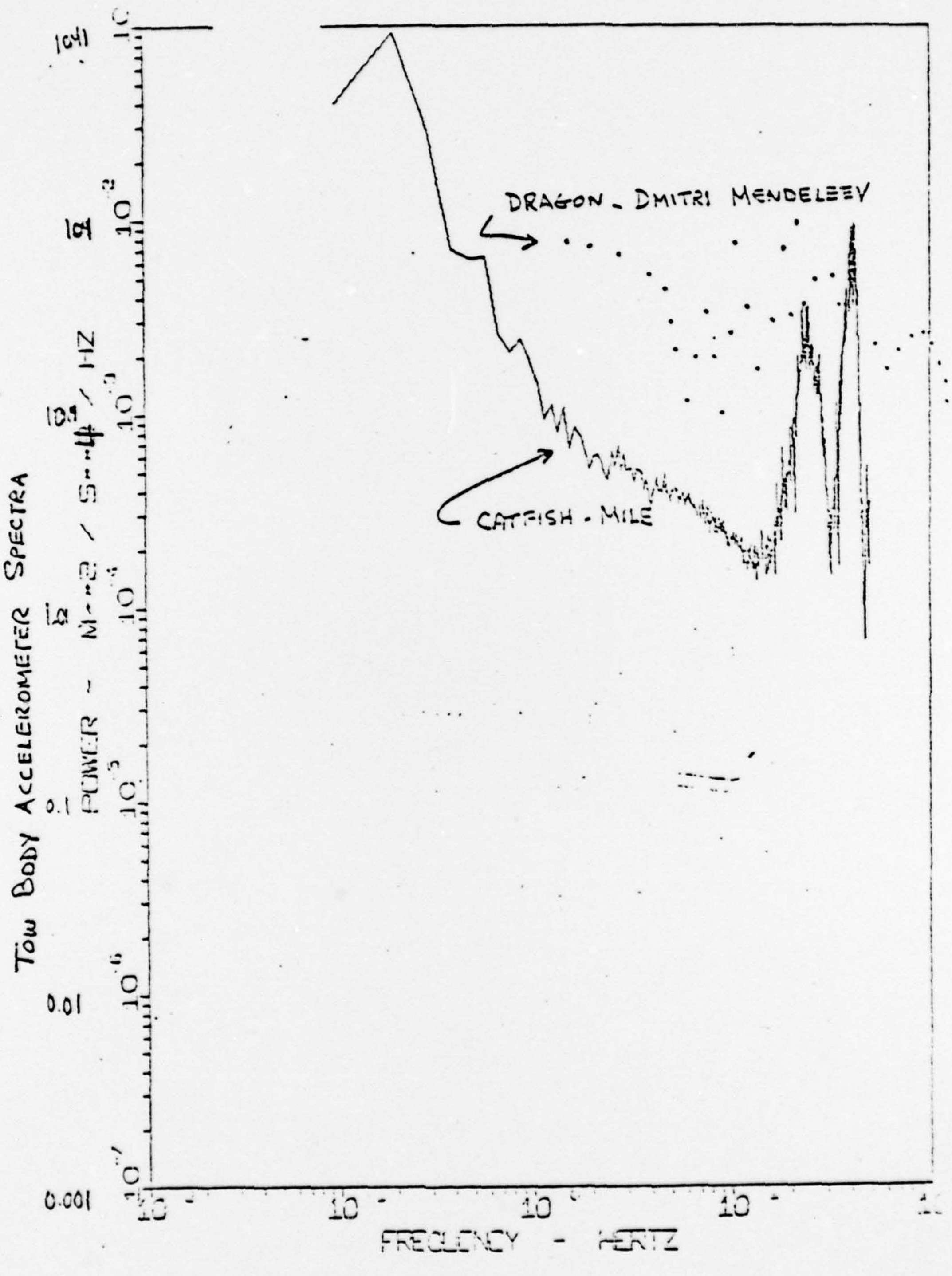
Pitch, Roll (Pendulum), Roll Rate and Linear Accelerometers (APL/JHU)

Speeds 3 knots, Depths 2 meters   July 9, 1977   San Diego

San Diego Test Motion Data. z-direction is vertical, x is along tow direction



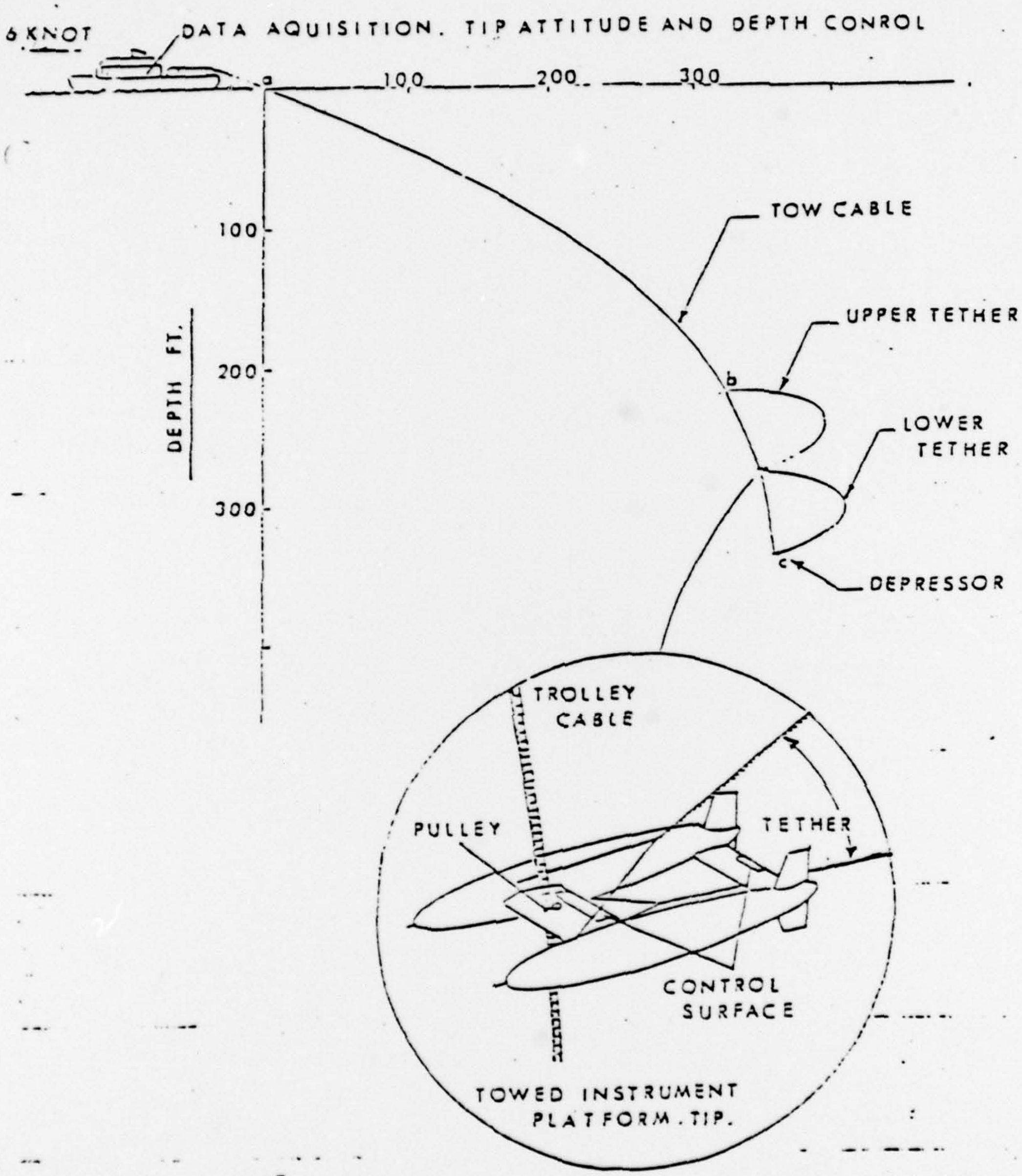
MILE Data



Accelerometer Spectra, Lead Weighted Tow Body Compared to Scripps System (CATFISH) during MILE

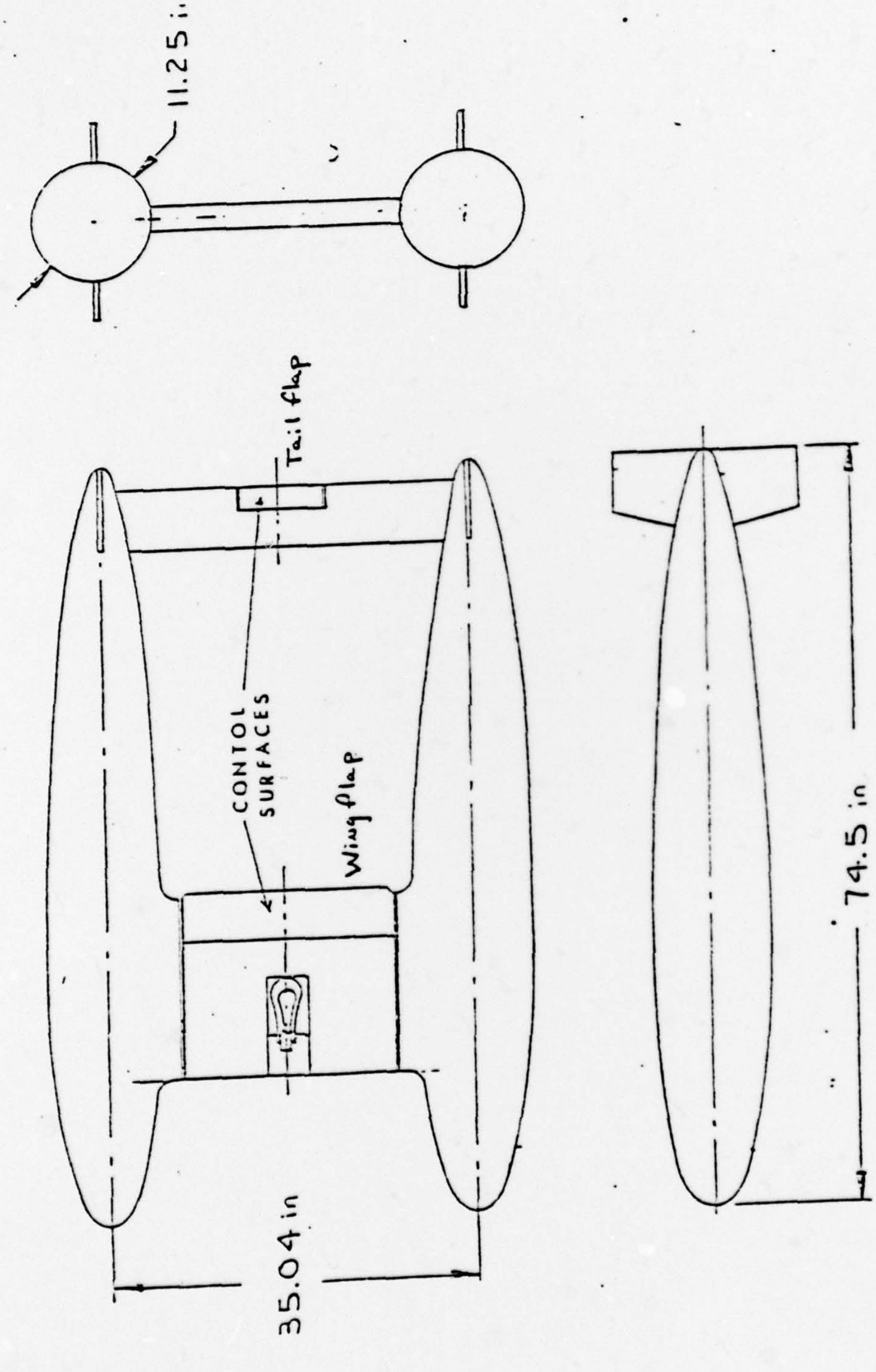
APL SYSTEM

Except for the four main differences mentioned in Section 3, the APL system is basically the same as the Scripps system. An additional difference, which is essentially an add-on, is the use of plastic fairing on the tow cable and a haired fairing on the tether cables rather than the nylon-velcro fairing. The following figures show an overall view of the system and various profiles of the body. Unfortunately, motion data from APL's recent sea test is not yet available for publication.



APL Towed Ocean Profiling System

APL System



TIP (Top, Side, and Front Views)